AD-A172 960

A NUMERICAL METHOD FOR UNFOLDING
THE STABILIZED NUCLEAR
CLOUD PARTICLE DISTRIBUTION

THESIS

James R. Felty, Captain, USA

AFIT/GNE/PH/86M-4

DTIC FILE COPY

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

DTIC
ELECTE
OCT 16 1986
S B D

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

86 10 10 07

0

AFIT/GNE/PH/86M-4

A NUMERICAL METHOD FOR UNFOLDING THE STABILIZED NUCLEAR CLOUD PARTICLE DISTRIBUTION

THESIS

James R. Felty, Captain, USA

AFIT/GNE/PH/86M-4

DTIC
ELECTE
OCT 16 1986
S D
B

Approved for public release, distribution unlimited

AFIT/GNE/PH/86M-4

A NUMERICAL METHOD FOR UNFOLDING THE STABILIZED NUCLEAR CLOUD PARTICLE DISTRIBUTION

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Nuclear Engineering

James R. Felty, B.S.
Captain, USA

MARCH
~~January~~ 1986

Approved for public release; distribution unlimited

Preface

In order to more accurately predict nuclear near and far field fallout effects, an accurate portrayal of the stabilized nuclear cloud particle size distribution is a necessity. However, there is a continuing debate over the nature of this distribution. During the late 1950s and 1960s much research was done using ground fallout samples to construct the nuclear cloud particle size distribution. Unfortunately, ground fallout samples cannot adequately describe the particle size distribution in the stabilized cloud and airborne sampling of our early events was scarce and poorly documented. Consequently, in most cases, the nuclear cloud particle size distribution currently being used by defense planners to predict fallout patterns of strategic importance is based on Marcel Nathans' 1970 publication of his work with nuclear cloud samples. Yet, aside from Nathans' work, little research has been done to derive a more accurate nuclear cloud particle size distribution from nuclear cloud samples.

The purpose of this independent study was to try a different approach to reconstructing the stabilized nuclear cloud particle size distribution from reduced airborne filter sample data. This method requires only one piece of reduced filter sample data, the total mass or the

total activity on the filter. It also uses a state-of-the-art stabilized cloud model and state-of-the-art particle fall mechanics.

Overall, this research was quite enjoyable. I would like to thank Dr. Charles J. Bridgman for his support and patience with me. Also, I am deeply indebted to my wife, [redacted], for her patience and understanding during the many hours needed to complete this work.

QUALITY INSPECTED 1

Accession For
NTIS GRA&I
DTIC TAB
Unannounced
Justification PER CALL JC
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

Table of Contents

List of Figures

List of Tables

Abstract

This study developed a numerical method of unfolding the particle size distribution of the stabilized nuclear cloud from reduced airborne filter sample data. A stabilized nuclear cloud is modeled using a trial particle size distribution that is positioned in the atmosphere by empirical relationships developed by Hopkins and Connors. Davies-McDonald fall mechanics are used to model the falling particles in the ~~nuclear~~ cloud. The amount of mass at each sample altitude, at each sample time is calculated from the cloud model and compared to the amount of mass found in ~~the~~ actual cloud samples. When the calculated masses equal the actual masses, the particle distribution used to construct the stabilized cloud is the correct one. A computer code for this numerical analysis is also presented.

The computer code is tested using hypothetical filter sample data constructed from a known particle size distribution. Additionally, an input parameter sensitivity analysis is conducted.

Actual nuclear cloud sample data from the Redwing series, shot ZUNI is analyzed using this numerical method of airborne nuclear cloud sample analysis. The outcome of the ZUNI sample analysis is somewhat inconclusive in that

it does not pinpoint a distribution. However, based on the results of the model sensitivity analysis, the ZUNI sample analysis indicates that the particle size distribution of the stabilized ZUNI cloud may be lognormal with a log-slope that is between 2.9 and 3.9, but is definitely not less than 2.7 nor greater than 5.0.

Finally, the theory for an alternative method of airborne sample analysis is presented. This method uses the relative number of particles of each size found in an airborne sample to unfold the stabilized nuclear cloud particle size distribution.

A NUMERICAL METHOD FOR UNFOLDING THE STABILIZED NUCLEAR CLOUD PARTICLE DISTRIBUTION

I. Introduction

Background

The ability to accurately model fallout patterns from nuclear bursts is largely dependent upon knowledge of the particle size distribution in the stabilized nuclear cloud. Bigelow's sensitivity analysis of lognormal particle size distributions versus fallout pattern predictions (3:V-15) graphically illustrates this fact. Moreover, he demonstrated that selection of the proper distribution standard deviation is very important because relatively small changes in this value produce changes of an order of magnitude or more in the size-activity distribution median. These size-activity median changes greatly affect the fallout prediction outcome (3:V-13). Consequently, the importance of selecting the proper nuclear cloud particle size distribution for fallout pattern modeling cannot be emphasized strongly enough.

Many proposed nuclear cloud particle size distributions can be found in the open literature. For the most part, these distributions were determined by evaluation of fallout samples from the many nuclear test shots in Nevada

and the Pacific ocean. Conners lists twelve such distributions in his study (7:11). Two of the most popular ones are the Defense Land Fallout Interpretive Code (DELFIC) default distribution and the so-called TTAPS distribution. These two lognormal particle size distributions are radically different, yet they were both derived from fallout sample data. Therefore, it is quite clear that there is still a great potential for debate about the nature of the stabilized nuclear cloud particle size distribution.

Another area of growing concern is over the potential differences in the particle size distribution calculated from analysis of "fallen" fallout samples and the actual "falling" particle size distribution in the nuclear cloud. Hopkins' analysis of the Mount St. Helens ash cloud determined that the particle size distribution calculated from "fallen" samples, collected on the ground, could not be used to adequately predict the observed ash fallout pattern (16:83-91). It is quite possible that this phenomenon is true of nuclear clouds as well.

Overall, the main issue here is that there is uncertainty surrounding every potential particle distribution used to describe the stabilized nuclear cloud. Since the selection of a proper particle size distribution is key to accurate fallout prediction it is imperative that every effort be made to accurately define a valid distribution. Therefore it is evident that analysis of "fallen" particle

samples, taken on the ground, must be used in conjunction with analysis of "falling" samples, taken in the cloud, in order to better qualify the actual particle size distribution in the nuclear cloud. This study is primarily concerned with the analysis of "falling" cloud samples.

Problem

Much effort has been made in analyzing the "fallen" fallout samples. However, aside from Nathans' work (Ref 19), little has been done to unfold the nuclear cloud particle size distribution from airborne "falling" samples. This study attempts to unfold the particle size distribution of the stabilized nuclear cloud through numerical analysis of airborne filter samples taken from nuclear clouds during atmospheric testing.

Scope

This study is limited in scope to examination of samples taken from nuclear clouds by aircraft. The model used here assumes a horizontal flight path through the center of the nuclear cloud at different altitudes and different times following cloud stabilization. The mass of material collected on the filter samples is then compared to what should have been on the filter samples given a hypothetical nuclear cloud particle size distribution.

The stabilized nuclear cloud is modeled as being gaussian in the "x-y" horizontal plane as well as gaussian

in the vertical or "z" direction. The particles are gravity sorted by size. In other words, each size group is lofted to its initial stabilized altitude and spatially positioned using Hopkins' and Conners' empirical relationships. No wind effects are considered. Only the forces of gravity and atmospheric viscosity act on the particles. Davies-McDonald fall mechanics are used to model particles falling through a non-homogeneous atmosphere.

Only surface bursts or near surface bursts are considered in this study. Surface bursts loft the most material and their nuclear clouds are believed to be better understood than clouds from near surface or air bursts.

Finally, the lognormal distribution is the only distribution considered as a potential nuclear cloud particle size distribution in this study. It is hypothesized that a reasonable fit can be achieved with a lognormal distribution (4:209). Moreover, numerical analysis of either the mass or activity distributions in the nuclear cloud is greatly simplified by the property of lognormal moments for a lognormal distribution.

Assumptions

Minor assumptions concerning specific procedures used in this study will be presented at appropriate places in the body of this report. However, the following are some general assumptions that apply throughout the work.

1. The stabilized nuclear cloud can be represented by a gaussian distribution of all particle sizes in the "x-y" horizontal plane. In the vertical or "z" direction the nuclear cloud can be modeled by using a finite number of particle size groups. Each group is represented by a mean radius and normally distributed in the vertical direction.

2. There is homogeneous mixing of particles horizontally within the cloud.

3. The particle size distribution in the stabilized nuclear cloud can be modeled with a lognormal distribution.

4. Gravity and atmospheric viscosity are the only forces acting on the particles in the stabilized nuclear cloud. No wind effects are considered.

5. All samples were taken under the same conditions; the same sampling apparatus was used for each sample. Additionally, the aircraft taking the samples was flown through the horizontal geometric center of the cloud at each respective sample altitude.

6. All fallout particles are assumed to be spherical. This assumption has little effect on fallout prediction (21:32).

7. The fallout density is assumed to be constant, 2600 kilograms per cubic meter, independent of particle size.

Approach and Sequence of Presentation

The computer model used for airborne filter sample analysis is developed in Chapter II in the following sequence. The stabilized nuclear cloud and falling cloud models are presented first. Next, the particle distribution calculative method is presented. Then, nuclear cloud sampling theory and integration of sampling into the falling cloud model are described. Finally, the method for determining the particle size distribution through falling particle sedimentation and numerical analysis of reduced filter sample data is presented in algorithm form.

In Chapter III, the model is validated by using calculated hypothetical filter samples from a known particle size distribution as input to the computer code presented in Chapter II. This code unfolds the stabilized nuclear cloud particle size distribution from the input filter sample data. Additionally, model sensitivity to input variations is presented and discussed in the final section of this chapter.

In Chapter IV, a study of actual airborne sample data from the Redwing series, shot ZUNI, is presented with results.

Finally, an alternative method of reconstructing the stabilized nuclear cloud particle size distribution from one or two airborne filter samples is presented in Chapter V.

Overall results and conclusions are found in Chapter VI.

II. Model Development and Theory

Background

Nuclear cloud particle formation is a complicated process that occurs during the time that the nuclear cloud is cooling. Initially, the nuclear detonation releases massive quantities of energy in a very short period of time. The resultant high temperature from x-ray deposition in the atmosphere creates a fireball that literally vaporizes everything within its boundaries. These vaporized materials include unfissioned weapons material, fission fragments, weapons case material, and any soil that was consumed by the fireball in the case of a surface or near-surface burst. As the fireball expands and rises, it cools and the highly refractory vaporized material begins to condense and form particles. Additional material may be transported up into the hot rising cloud by updrafts created by the rapidly rising hot cloud. Generally, much of this material is not completely vaporized. Once in the cloud, these particles grow in size as the more volatile elements, still in a vapor state, plate-out on their surfaces. The volatile material continues to plate-out on the surfaces of all particles in the cloud until the cloud temperature achieves an equilibrium with ambient temperatures.

Stabilization occurs when the hot nuclear cloud has cooled to the point where it stops rising. Regardless of yield, stabilization usually occurs within 5 to 7 minutes after the detonation. However, the greater the weapon yield, the higher its cloud will rise prior to stabilization. For example, the cloud from a 10 kiloton weapon, surface burst, will stabilize at approximately 5000 meters, whereas the cloud from a 1 megaton surface burst will stabilize at approximately 13000 meters (14:431). Since the scope of this study is limited to times following cloud stabilization, and is primarily concerned with the vertical distribution of particles in the cloud, the results of a cloud rise model to be used in this study are described in the next section.

Stabilized Cloud Model

The altitude to which a particle will rise depends on the weapon yield and the particle mass. For example, the smaller, less massive particles are lofted higher by the hot rising cloud than the larger more massive particles. Additionally, because of the assumption that the nuclear cloud is gaussian in the vertical direction, all particles of a given size are assumed to be normally distributed in the vertical direction. Hence, the gravitational sorting and particle vertical distribution assumptions lead to a cloud rise algorithm for modeling the stabilized cloud. This algorithm uses empirical relationships, presented in

Appendix A, to calculate the lofted altitude of the center of a vertical gaussian distribution and standard deviation for each different particle size being considered. In reality, there are a great number of particle sizes, therefore, an equally large number of vertical gaussian distributions to be lofted and characterized. However, this study initially limits the number of particle size groups used to at least the number of cloud samples being evaluated and at most eight.

An illustrative conception of the vertical distribution in the stabilized cloud is found in Figure 1. A gaussian for each of three particle size distributions is shown. The highest gaussian represents the smallest particles.

Particle Fall Mechanics

The force of gravity eventually overcomes the forces that are causing the particles to rise and they begin to fall from the cloud. The spherical particle assumption simplifies the problem and allows a particle's fall velocity to be calculated based on its radius and altitude. This process would be further simplified if all particle radii were less than about 10 micrometers because Stokes law applies to particles with radii less than 10 micrometers falling through the atmosphere. However, for particles larger than 10 micrometers, aerodynamic drag must be considered. Therefore, the following balance of forces equation applies (4:212):

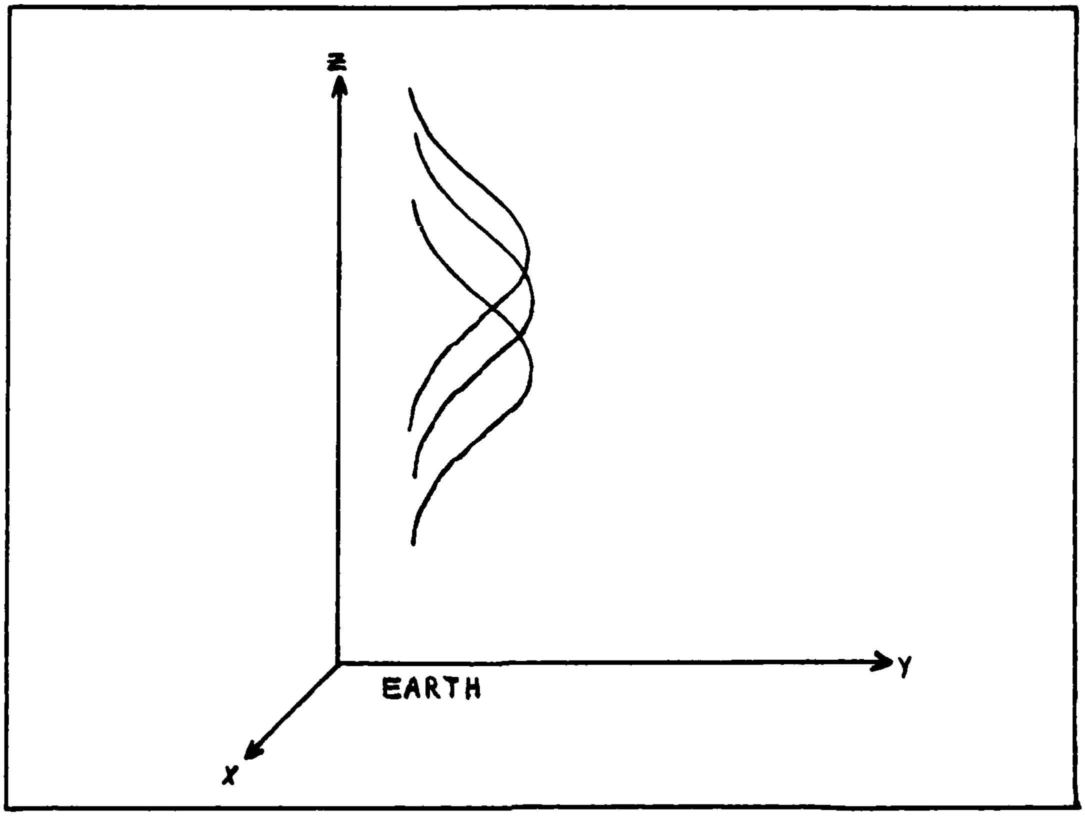

Fig. 1. Stabilized Cloud Particle Size Spatial Representation

$$\frac{1}{2}\rho_a v^2 C_d \pi r^2 = \frac{4}{3}\pi r^3 \rho_f g \qquad (1)$$

where

ρ_a = air density at the particle's altitude in kilograms/cubic meter

v = particle velocity in meters/second

C_d = drag coefficient

r = particle radius in meters

ρ_f = particle density in kilograms/cubic meter

g = gravitational constant in meters/second squared

Since the drag coefficient is also a function of particle velocity, Equation (1) cannot simply be solved for the particle velocity. However, the Reynolds number for falling spheres is (18:464):

$$R = \frac{2v\rho_a r}{\eta} \tag{2}$$

where

v = particle velocity in meters/second

ρ_a = air density at the particle's altitude in kilograms/cubic meter

r = particle radius in meters

η = dynamic viscosity of the air at the particle's altitude in kilograms/meter-second

Equation (2) can be solved for velocity and substituted into Equation (1). With some algebraic manipulation, this yields:

$$R^2C_d = \frac{32\rho_a\rho_f gr^3}{3\eta^2} \tag{3}$$

Davies (8:259-270) related the quantity R^2C_d to the Reynolds number by the following two empirical relationships:

$$R = \frac{R^2C_d}{24} - 2.3363 \times 10^{-4} (R^2C_d)^2 + 2.0154 \times 10^{-6} \times (R^2C_d)^3 - 6.9105 \times 10^{-9} (R^2C_d)^4$$

$$\text{for } R < 4;\ R^2C_d < 120 \tag{4}$$

$$\mathrm{LOG}_{10}(R) = -1.29536 + 0.986\,\mathrm{LOG}_{10}(R^2C_d) - 0.046677$$

$$\times\ [\mathrm{LOG}_{10}(R^2C_d)]^2 + 0.0011235\ [\mathrm{LOG}_{10}(R^2C_d)]^3$$

$$\text{for } 3 < R < 10000 \qquad (5)$$

The Reynolds number, calculated from these empirical relationships, can be used in Equation (2) to solve for the particle velocity.

Finally, a slip-drag correction factor (22:6)

$$SD = 1 + 1.165 \times 10^{-7}/r\rho_a \qquad (6)$$

is used to correct the falling velocities of the particles at high altitudes for their reduced interactions with air molecules (4:212). The variables r and ρ_a are the same as defined in Equation (2).

Now that the fall velocity can be calculated for any particle based on its radius and altitude, the distance traveled by a particle, DZ, is simply

$$DZ = v * \Delta t * SD \qquad (7)$$

where Δt is the time increment in seconds for which the particle falls.

The following algorithm, based on the above discussion, is used in this study to model particle gravitational fall:

1. U.S. Standard Atmosphere is used to calculate the air density and dynamic viscosity for each particle altitude.

2. R^2C_d is calculated using Equation (3).

3. With R^2C_d the Reynolds number is calculated using Equation (4) or Equation (5).

4. The Reynolds number is used in Equation (2) to determine the particle velocity.

5. The particle velocity is corrected for slip-drag by Equation (6).

6. The distance fallen is calculated using Equation (7) given an increment of fall time. This distance is subtracted from the particle's altitude yielding a new particle altitude.

7. If the particle has fallen for the desired time, the sequence is stopped; if not, the sequence is repeated for additional time increments until the total desired fall time is accomplished.

The optimum time increment must be selected so that computer time is conserved, yet sufficient accuracy is achieved. Obviously, selection of too long of a time increment results in inaccuracies because of variations in atmospheric properties with decreasing altitude. However, selection of too short of an increment results in a superfluous number of iterations with no notable increase in accuracy. Conners (7:120) suggested that a time increment

be selected so that the largest particle being considered not fall more than 1400 meters during that time increment. His empirical testing determined that this technique produced the largest time increment that did not significantly affect the calculated distance for the fall of particles. Therefore, in this particle fall model, the time-of-fall increment will be selected based on the time it takes for the largest particle size being considered to fall 1400 meters.

Lofted Particle Number Size Distribution

Given that all the previous assumptions are plausible, one final assumption is needed to complete the model. The lofted particle number-size distribution is assumed to be lognormal (4:210):

$$N(r) = \frac{N_t}{\sqrt{2\pi}\ \beta r}\ e^{-\frac{1}{2}\left(\frac{\ln r - \alpha_o}{\beta}\right)^2} \tag{8}$$

where

$N(r)$ = the number of particles with radius r

N_t = the total number of particles

β = the distribution log-slope

r = particle radius in micrometers

α_o = the natural log of the distribution median radius, r_o

The lognormal distribution is a universal assumption in approximating nuclear cloud particle size distribution (12:7).

Of course, one very useful property of the lognormal distribution is that the moments of the distributions are also lognormal distributions (2:12). For example, the third moment of the lognormal number-size particle distribution in Equation (8) is also a lognormal distribution. This is the mass-size distribution:

$$M(r) = \frac{M_t}{\sqrt{2\pi}\ \beta\, r}\ e^{-\frac{1}{2}\left(\frac{\ln r - \alpha_3}{\beta}\right)^2} \tag{9}$$

where

$M(r)$ = the total mass of all the particles with radius r

M_t = the total mass lofted by the weapon

$\alpha_3 = \alpha_o + 3 * \beta^2$

All other parameters are the same as defined above following Equation (9).

When integrated, Equation (9) yields the total mass aloft. By using a function that approximates the cumulative lognormal distribution, the mass moment can be divided into any number of equal mass groups (1:932). Then the median radius for each equal mass group can be used to represent the entire group in a particle fall mechanics code.

Cloud Sampling Theory

Given that at stabilization each equal mass particle group can be represented by a gaussian distribution in the vertical direction, as depicted in Figure 1, after stabilization, these same groups will fall under the influence of gravity. As expected, the smaller particles are not only lofted higher than the larger particles, but settle slower than the larger particles. Figure 2 illustrates this concept.

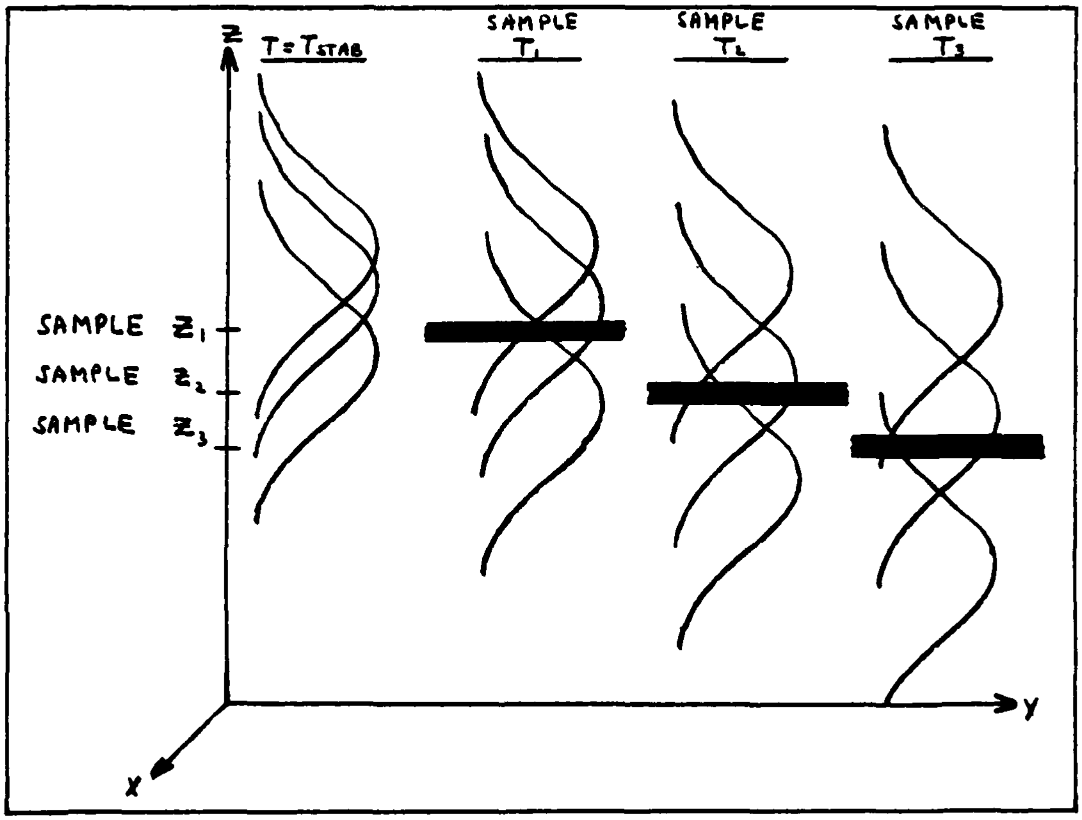

Fig. 2. Gravitational Settling of Different Particle Sizes

Figure 2 also graphically illustrates how cloud samples taken at different altitudes and different times intersect the various particle vertical gaussian distributions as they fall with time. This concept is the key to the theory behind this study's analysis of airborne samples. Simply stated, the total mass of material in an airborne sample is equal to the sum of the contributions of mass from each equal mass group's vertical distribution collected by the sampling system as it passed through the nuclear cloud. This can be mathematically stated:

$$S = \sum_{i=1}^{n} G_i \tag{10}$$

where

S = sample total mass

n = number of equal mass groups considered (also equal to the number of airborne samples being analyzed)

G_i = total mass contributed by each equal mass group

The total mass contributed by each group, G_i, is further defined as:

$$G_i = A * F_i * M_t \tag{11}$$

where

A = fraction of total mass aloft contained in group i

F_i = gaussian fraction of group i at the sample altitude and time

M_t = total mass lofted by the weapon

Note that if the correct particle mass distribution is used, then the "A" values are all equal since equal mass groups were assumed initially.

If a number of samples are taken at different altitudes and at different times, the resulting set of equations can be written:

$$A_1F_{11}M_t + A_2F_{12}M_t + \dots A_nF_{1n}M_t = S_1 \tag{12}$$

$$A_1F_{21}M_t + A_2F_{22}M_t + \dots A_nF_{2n}M_t = S_2 \tag{13}$$

$$\vdots \qquad \vdots \qquad \vdots \qquad \vdots$$

$$A_1F_{n1}M_t + A_2F_{n2}M_t + \dots A_nF_{nn}M_t = S_n \tag{14}$$

where, in the case of these equations,

n = the number of airborne samples being analyzed

$S_{(1\ \text{to}\ n)}$ = samples, each taken at a different altitude and time

$A_{(1\ \text{to}\ n)}$ = the fraction of the mass aloft contained in each group

$F_{(1\ \text{to}\ n,\ 1\ \text{to}\ n)}$ = the gaussian fraction of each group at each sample altitude, at each sample time

M_t = total mass lofted by the weapon

The total mass on "n" airborne samples, or "S" values, are known. By using the stabilized cloud model described above, and allowing "n" equal mass groups to fall in accordance with the fall mechanics described above, the gaussian fraction, or "F" value of each of the equal mass groups can be calculated for each sample altitude and time. The fractions of mass aloft contained in "n" equal mass groups, or "A" values, are the unknowns. Consequently, this type of analysis yields "n" simultaneous equations with "n" unknowns that can be expressed in a simple matrix equation:

$$M_t[F] \times [A] = [S] \tag{15}$$

where

F = n x n matrix (calculated)

A = n x 1 matrix (unknowns)

S = n x 1 matrix (sample values)

If this equation is multiplied by the inverse of the "F" matrix, it yields a solution for the "A" vector. If the solution yields equal "A" values, then the fraction of the total mass lofted, in each group, is the same. Since the assumed particle distribution was initially divided into equal mass groups, and the calculated fraction of mass per group is the same, then the assumed particle distribution is the correct one.

The solution of Equation (15) is the final major step in determining the particle size distribution for the stabilized nuclear cloud. From now on, this method will be referred to as the integral method, since it attempts to unfold the stabilized cloud particle distribution by summing the contribution from falling equal mass groups to determine the total sample mass. The next section outlines the code used to do the distribution search thereby integrating all the previously discussed theory into a distribution search algorithm.

Airborne Sample Analysis Code for the Integral Method

A computer program was developed to numerically analyze airborne cloud sample data and determine a particle distribution for the stabilized cloud. This program was written in FORTRAN-5 (FORTRAN-77) and run on a CYBER 170-845. The program is called SEARCH4. Basically, SEARCH4 reads a log-slope and initial median radius from a data file called SEARCH. Then, it varies the median radius through a range of values, creating a number of different lognormal distributions. Each distribution is checked by the algorithm listed below. The log-slopes in the data file SEARCH vary from 1.5 to 5.0. The median radii range of values is selected so that the equal mass group mean radii calculated from each lognormal distribution make

physical sense. A copy of the code, example input files, and glossary of program variables are included in Appendix B.

The algorithm contained in the program is as follows:

1. Airborne sample data, sample total mass, time of collection, and collection altitude, are read from a file "FILTER."

2. The first set of lognormal distribution parameters is read from a file "SEARCH."

3. A lognormal distribution, defined by a log-slope, β, and a median radius, r_o, is divided into "n" equal mass groups and a median radius for each of the groups is calculated.

4. The largest median radius is used to calculate the fall time increment.

5. Each group represented by a vertical gaussian with that group's median radius is empirically lofted to its stabilized altitude and allowed to fall until the time of the first sample. The gaussian is evaluated at the first sample altitude to determine the fraction of total mass in this group being contributed to the total sample mass. The mass contributed by this group is stored in an array, F_{ij}.

6. The procedure in (5) is repeated for each group, once for each sample. The resultant array, F_{ij}, is the "F" matrix, discussed in the previous section.

7. The "F" matrix is inverted and multipled times the "S" vector to solve Equation (15) for the fraction of mass in each group, or "A" values.

8. The "A" values are compared to each other by least squares standard deviation and only those with a low standard deviation are written to the output file "ANSWER" along with the lognormal distribution parameters for that iteration.

9. A new set of lognormal distribution parameters are read from the input file "SEARCH" and the entire process is repeated.

In summary, here is an example that will demonstrate the integral method theorized throughout Chapter II and described in the algorithm in this section: If 3 airborne sample masses are to be analyzed, then a trial lognormal mass-size distribution, characterized by a log-slope and a median radius, is divided into 3 equal mass groups. A median radius for each of the equal mass groups is calculated and used to represent all the mass in its group. Then, each of the equal mass groups, with median radius, represented by a vertical gaussian, is allowed to fall from its stabilized altitude until each sample time. The vertical gaussian is evaluated at the sample altitude to

determine what fraction of the mass represented by that group is contributed to the total mass in the sample. Now, all the elements for Equation (15) are present and the matrix equation can be solved for the fraction of mass in each group, or the "A" values. If the "A" values are all equal, then the trial mass-size distribution is the correct one.

III. Integral Model Validation

Background

Prior to analyzing airborne filter sample data from an actual nuclear shot, the integral model presented in Chapter II was validated using hypothetical sample data created with a known particle distribution. The purpose of this validation was twofold. First, the obvious reason for controlled testing of the model was to insure that it would function as predicted. Second, and perhaps of equal importance, was the need to conduct a rudimentary sensitivity analysis of the model's solution given controlled variation of the input parameters. This chapter explicitly presents the numerical experiment used to validate the integral model.

The general approach to the first part of this numerical experiment is as follows: A modified version of the SEARCH4 program is used to create hypothetical masses on three airborne filter samples given fixed input parameters. Then, these sample masses are used as input to the SEARCH4 program for analysis. If the program functions properly, the output solution vector, consisting of three "A" values (fraction of mass in each mass group) will have a minimum standard deviation when the lognormal distribution

parameters being checked by SEARCH4 match the lognormal parameters used to create the samples.

The second part of the numerical experiment uses the sample data created in the first part as a base case and varies input parameters, one at a time, to study the effect on the output solution vector. The parameters to be varied are chosen because they are the ones that are most likely to be different in an actual cloud sampling situation from what was assumed in this model. These variable parameters include the falling particle density; the weapon yield; the total mass lofted by the weapon, and the following sample input data: sample total mass, time of collection, and collection altitude.

Further details concerning the numerical experiment and results are contained in the following sections of this chapter.

Integral Method Numerical Validation Experiment

The modifications made to the SEARCH4 program in order to make it produce hypothetical filter sample data can best be described by using the nine step program algorithm presented in the final section of Chapter II. The procedure involves changing steps one, two, three, and five of the algorithm, and eliminating steps seven through nine completely. Step one is changed so that the need to input a total sample mass is eliminated. Step two is

changed to an interactive sequence that requests a median radius and log-slope for the "known" lognormal particle number-size distribution to be used throughout the numerical experiment. Step three is modified so that the distribution is divided into 50 equal mass groups. Finally, step five is altered in two ways. The masses contributed by each equal mass group are summed for each different sample time and altitude and stored in an array. Each of these values represents a hypothetical total mass on an airborne filter sample taken at a given altitude and a given time. Last of all, these newly created airborne filter sample masses are written to the ANSWER file for output.

The decision to use 50 equal mass groups to create the hypothetical filter sample data is based on numerical experimentation fostered by the following reasoning. Since, in reality, the stabilized nuclear cloud contains a great number of particle sizes, 50 equal mass groups represented by 50 different median radii more validly approximate the actual falling cloud than only a few equal mass groups with only a few median radii. Additionally, one of the goals of this validation experiment was to test the program's ability to analyze actual sample data. It was learned through numerical experimentation that if filter sample masses were created using only a few equal mass groups, this procedure not only failed to validly approximate nature, but also failed to challenge the program.

Consequently, numerical experimentation was used to determine the optimum number of equal mass groups to use in creating realistic filter sample data. Filter sample masses were created with a varying number of equal mass groups. Sample masses created with 3 to 15 equal mass groups varied numerically in the first and second significant figures. Those sample masses created using 15 to 50 equal mass groups varied in the second and third significant figure, and beyond 50 equal mass groups, the differences were in the fourth and fifth significant figures. Therefore, it can be argued that 50 equal mass groups can be used to adequately represent the actual falling nuclear cloud for the purposes of this experiment.

The Defense Land Fallout Information Code (DELFIC) default spectrum lognormal parameters, median radius, r_o = 0.204 micrometers, and log-slope, $\beta = \ln(4)$ (4:210) are used throughout this numerical experiment. This choice is made for no reason other than the fact that the DELFIC default distribution is one that is widely used in fallout modeling. The other input is arbitrarily selected as representative of a typical nuclear cloud sampling project. Table I lists the input data for the modified version of SEARCH4 and Table II lists the output filter sample data.

The calculated filter sample masses listed in Table II are considerably larger than expected. This is because they represent a clean sweep of all the mass per

TABLE I

PROGRAM INPUT DATA FOR INTEGRAL MODEL VALIDATION, PART ONE

Yield (mt)	Total Mass Lofted (kg)	Sample Altitude (m)	Sample Time (min)
		13100	182
3.5	1.06×10^9 (*)	15800	152
		16200	184

(*) Note: Mass lofted based on one-third of a ton of mass lofted per ton of yield. Additionally, the density of this material is assumed to be 2600 kilgrams per cubic meter.

TABLE II

CALCULATED HYPOTHETICAL FILTER SAMPLE DATA

Sample Altitude (m)	Sample Time (min)	Sample Total Mass (kg)
13100	182	41126
15800	152	47636
16200	184	42575

vertical meter in the nuclear cloud at their respective altitudes and at their respective times of collection. If the assumptions that all samples were taken under the same conditions and the aircraft flew through the geometric center of the cloud at each altitude are valid, then no correction factors are needed to correct for different cloud penetration flight paths or for different sampling air flow rates. That being the case, the magnitudes of the individual sample masses are not important. What is important is the ratio of the samples, one to another.

The data from Tables I and II was input to the SEARCH4 program and a quick search was conducted of log-normal distributions with log-slopes of 1.5 to 5.0. The first search revealed no solution vectors with standard deviations less than 100. In this case, a marginal solution occurred because of the relatively high altitudes and late times of the samples. Most of the large particles had already fallen from the cloud. At 3 hours after stabilization, for a 3 megaton burst, particles with radii of 80 micrometers are hitting the ground (6:67). Therefore, the majority of the particles larger than 80 micrometers have already fallen to earth, or at the very least, are not present at the high sample altitudes. Yet, by using only three equal mass groups in the search, the model is limited to working with group median radii of 17, 65, and 250 micrometers. It's doubtful that any 250 micrometer

particles are at these high sample altitudes at 3 hours after cloud stabilization. Consequently, a marginal solution was understandable.

One solution to the large particle dilemma is to divide the mass aloft into more equal mass groups. Then only the first three groups, or the ones with the smallest median radii are used. For example, in this experiment, the mass moment of the lognormal distribution representing the total mass aloft was divided into six equal mass groups. Their mean radii were, 9.6, 25.6, 48.6, 87, 166, and 443 micrometers. Since the majority of the particles with the three largest radii have fallen well below the sampling altitudes during the 3 hours prior to sampling, the 50 percent of the lofted mass contained in these groups does not contribute to the samples. Therefore, since only the first three groups are contributing to the samples, and they contain only 50 percent of the mass aloft, each of the solution vector values should be 0.1667, or one-sixth of the mass aloft.

Before any program output is presented, an explanation of the method of presentation is necessary. All program output tabulated throughout this study is presented in the following format: Each potential solution distribution is tabulated in terms of its characteristic parameters, median radius and log-slope. Additionally, the solution vector of "A" values and a standard deviation of these "A"

values from their algebraic mean are presented for every potential solution distribution.

Table III contains the output from a search conducted with the program SEARCH4 and six equal mass groups. Nine potential solutions were found by the program. However, the solution with beta = 4 and the median radius = 0.2 is the only one that has two solution vector elements closest to the expected value of 0.1667.

Two additional searches were conducted in an attempt to pinpoint the distribution with the closest fit. One search used seven equal mass groups and the other used eight. Also, both of these searches used a finer mesh of lognormal median radii, thereby checking ten times as many distributions as were checked by the previous six group search.

Since the total mass aloft is now being divided into seven and eight equal mass groups, the expected solution vector values are 0.143 and 0.125 respectively. Also, by dividing the mass aloft into a greater number of groups, and then using only the first three groups for the sample analysis, implicitly, more mass is assumed to have fallen from the cloud and not to have contributed to the samples. For example, in the seven group analysis, 57 percent of the mass is assumed to be on the ground, or at least below the sampling altitudes prior to the sampling times. Likewise, for the eight group analysis, 62 percent of the mass

TABLE III

SIX EQUAL MASS GROUP PARTICLE DISTRIBUTION SEARCH RESULTS

INPUT SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
2.0	2.9	.4935933E-01

SOLUTION VECTOR
.2135982E+00
.1254121E+00
.1310807E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
1.0	3.1	.1432091E-01

SOLUTION VECTOR
.1442953E+00
.1344202E+00
.1160741E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
1.0	3.2	.2219986E-01

SOLUTION VECTOR
.1822619E+00
.1421405E+00
.1457329E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
1.0	3.3	.4534747E-01

SOLUTION VECTOR
.2292991E+00
.1386594E+00
.1867187E+00

TABLE III--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.5	.1805175E-01

SOLUTION VECTOR
.1453390E+00
.1644582E+00
.1283762E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.30	3.8	.4363031E-01

SOLUTION VECTOR
.1665152E+00
.1587127E+00
.2378811E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.20	4.0	.5155210E-01

SOLUTION VECTOR
.1577227E+00
.1657446E+00
.2507538E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.11	4.3	.6384798E-01

SOLUTION VECTOR
.1442388E+00
.1768401E+00
.2674626E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.090	4.4	.6300539E-01

SOLUTION VECTOR
.1370042E+00
.1825519E+00
.2615282E+00

is assumed to be below the sample altitudes at sampling times. These assumptions may be acceptable at later times but they become less valid as the time between cloud stabilization and sampling is decreased. At these early times following stabilization many larger particles are still aloft.

In the seven group search, the number of potential solution vectors was reduced from the nine listed in Table III to the six listed in Table IV. However, the solution vector for the distribution with the log-slope equal to four had a slightly lower standard deviation than any of the others listed in the table. On the other hand, the individual solution vector elements for this distribution do not closely approach their expected values of 0.143 as they did in the six group search. Nonetheless, based on the data in Tables III and IV, the best estimate of the actual stabilized cloud distribution at this point is that it is lognormal with a log-slope somewhere between 3.9 and 4.1, and a median radius between 0.19 and 0.28 micrometers.

The last search conducted is the eight group search. In this search, the number of potential solution vectors was reduced from the six listed in Table IV to the four listed in Table V. This time, all the solution vectors' elements are close to the expected value of 0.125, with the exception of the last distribution. Overall, the potential

TABLE IV

RESULTS FROM THE SEVEN EQUAL MASS GROUP SEARCH

INPUT SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.42	3.6	.8528267E-02

SOLUTION VECTOR
.1362968E+00
.1367865E+00
.1217763E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.34	3.7	.7654989E-02

SOLUTION VECTOR
.1313907E+00
.1387913E+00
.1234842E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.34	3.8	.9797272E-02

SOLUTION VECTOR
.1598086E+00
.1563453E+00
.1413748E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.28	3.9	.6429054E-02

SOLUTION VECTOR
.1570277E+00
.1594050E+00
.1472728E+00

TABLE IV--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.23	4.0	.6360630E-02

SOLUTION VECTOR
.1531412E+00
.1629241E+00
.1509903E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.19	4.1	.747499E-02

SOLUTION VECTOR
.1507499E+00
.1656834E+00
.1576448E+00

TABLE V

RESULTS FROM THE EIGHT EQUAL MASS GROUP SEARCH

INPUT SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.27	3.9	.7414105E-02

SOLUTION VECTOR
.1391024E+00
.1327621E+00
.1243237E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.22	4.0	.4736288E-02

SOLUTION VECTOR
.1358764E+00
.1329348E+00
.1266077E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.18	4.1	.3188375E-02

SOLUTION VECTOR
.1324259E+00
.1343090E+00
.1280913E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.19	4.2	.9649241E-02

SOLUTION VECTOR
.1696385E+00
.1531179E+00
.1700169E+00

solutions found by SEARCH4 during this eight group search echo the findings of the seven group search. Namely, the particle size distribution for the hypothetical stabilized nuclear cloud that the calculated filter samples came from is a lognormal distribution with a log-slope between 4.0 and 4.1 and a median radius between 0.18 and 0.22 micrometers.

In summation, the integral method of unfolding the stabilized nuclear cloud particle size distribution from airborne filter sample data was tested in this section using filter sample data created from a hypothetical nuclear cloud. This hypothetical nuclear cloud's particle size distribution was the DELFIC default particle size distribution. Since the SEARCH4 program predicted a particle size distribution that was quite close to the "known" distribution, used to create the filter samples, it can be argued that the integral model is a valid method for determining the particle size distribution of a stabilized cloud, or at least a valid method for determining the distribution log-slope.

The next section of this chapter presents a detailed sensitivity analysis of the model using the data in Table V as base case data.

Integral Method Numerical Sensitivity Analysis

Many of the measurements made during the atmospheric nuclear tests produced data that were not as accurate or as well documented as that which is needed for the integral model. For example, perhaps the actual flight path of the sampling aircraft did not pass through the geometric center of the nuclear cloud. In most cases, no specific notes on the flight path were made aside from aircraft altitude and time in the cloud. Also, many clouds from megaton sized weapons were only peripherally sampled. Since this model assumes a flight path through the geometric center of the nuclear cloud at every sampling altitude, a difference between the actual flight path and the assumed flight path may change the program output considerably.

Consequently, the purpose of this part of the integral model testing is to determine how sensitive the model is to small inaccuracies in the input parameters. The calculated filter sample masses from Table II, and the results of the eight equal mass group search from Table V are used as a base case for this sensitivity analysis. Each of the program input parameters is varied, one at a time, and the effects on the output distribution parameters and solution vectors are analyzed.

The first parameter to be varied is the particle density. The particle density used in calculating the filter sample masses found in Table II was the integral model default value, 2600 kilograms per cubic meter. In this numerical experiment, the density input to SEARCH4 is varied from 2300 kilograms per cubic meter to 2900 kilograms per cubic meter. The resultant distribution parameters and solution vectors for the search conducted using a fallout density of 2300 kilograms per cubic meter are listed in Table VI. The results of the search conducted using a fallout density of 2900 kilograms per cubic meter are listed in Table VII. When the assumed particle density is varied by approximately 10 percent, either up or down, the predicted distribution log-slope and median radius remain relatively unchanged. For example, from Table V, with the fallout density set at 2600 kilograms per cubic meter, the optimum distribution is one with a log-slope between 3.9 and 4.2, and a median radius between 0.18 and 0.27 micrometers. For both fallout densities of 2300 and 2900 kilograms per cubic meter, the optimum distribution is one with a log-slope between 3.6 and 4.2, and a median radius between 0.2 and 0.5 micrometers. Therefore, it is evident that small changes in the fallout particle density do not significantly effect the integral model output. This is as expected because varying the particle density by 10 percent in Equation (3) affects all falling particles

TABLE VI

RESULTS FROM PARTICLE DENSITY VARIATION NUMERICAL EXPERIMENT FOR DENSITY = 2300 KILOGRAMS PER CUBIC METER

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.6	.1295183E-01

SOLUTION VECTOR
.1429085E+00
.1224889E+00
.1188954E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.7	.3043482E-01

SOLUTION VECTOR
.1663867E+00
.1491839E+00
.1072196E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.8	.3852854E-01

SOLUTION VECTOR
.2155282E+00
.1387422E+00
.1827281E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.30	3.9	.3421003E-01

SOLUTION VECTOR
.1241103E+00
.1663406E+00
.9860537E-01

TABLE VI--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.30	4.0	.1727375E-01

SOLUTION VECTOR
.1784879E+00
.1497153E+00
.1475411E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.30	4.1	.4048359E-01

SOLUTION VECTOR
.2236078E+00
.1468642E+00
.1628847E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.20	4.2	.1022544E-01

SOLUTION VECTOR
.1655476E+00
.1577415E+00
.1452745E+00

TABLE VII

RESULTS FROM PARTICLE DENSITY VARIATION NUMERICAL EXPERIMENT FOR DENSITY = 2900 KILOGRAMS PER CUBIC METER

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.6	.1956538E-01

SOLUTION VECTOR
.1578669E+00
.1342443E+00
.1190391E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.50	3.7	.3570383E-01

SOLUTION VECTOR
.1994141E+00
.1337939E+00
.1909921E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.30	3.9	.1256950E-01

SOLUTION VECTOR
.1619730E+00
.1467839E+00
.1370307E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.20	4.1	.9405460E-02

SOLUTION VECTOR
.1501645E+00
.1543116E+00
.1363482E+00

equally, and therefore would have little effect on the output from SEARCH4.

The second parameter to be varied is the yield. Since the cloud rise portion of the model is heavily dependent upon the weapon yield in order to position the particle groups at their initial stabilized altitudes, a difference between the actual yield and the assumed yield could affect the program's output.

For this numerical experiment, the yield used to create the filter samples found in Table II was varied from 3 megatons to 4 megatons. The resultant distribution parameters and solution vectors are listed in Tables VIII and IX. Again, no significant changes in the SEARCH4 output are discernible as the yield is varied up to 15 percent in either direction. The SEARCH4 program still selects an optimum distribution with a log-slope between 3.7 and 4.4, and a median radius between 0.1 and 0.5 micrometers.

Regardless of a slight yield variation, stable program output is understandable for the following reasons. In this case, an increase or decrease in yield of half a magaton only changes the particles' initial altitudes by about 500 meters for particles in the 10 to 150 micrometer size range. This small initial altitude change produces only a minor difference in the mass per vertical meter at the sample altitudes. Additionally, given one set of

TABLE VIII

RESULTS FROM WEAPON YIELD VARIATION NUMERICAL EXPERIMENT
FOR YIELD = 3 MEGATONS

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.0	.2562264E-01

SOLUTION VECTOR
.1302901E+00
.1353253E+00
.8864276E-01

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.2	.4721363E-01

SOLUTION VECTOR
.2074971E+00
.1237366E+00
.1278609E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.11	4.3	.2247532E-01

SOLUTION VECTOR
.1204685E+00
.1391976E+00
.9444473E-01

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.09	4.4	.1906333E-01

SOLUTION VECTOR
.1196479E+00
.1364339E+00
.9839454E-01

TABLE IX

RESULTS FROM WEAPON YIELD VARIATION NUMERICAL EXPERIMENT
FOR YIELD = 4 MEGATONS

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	3.7	.1090653E-01

SOLUTION VECTOR
.1683339E+00
.1532609E+00
.1744525E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	3.9	.9227757E-02

SOLUTION VECTOR
.1459867E+00
.1428191E+00
.1601487E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	4.0	.6607308E-01

SOLUTION VECTOR
.1824687E+00
.1536467E+00
.2797444E+00

TABLE IX--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.1	.2396100E-01

SOLUTION VECTOR
.1536515E+00
.1277581E+00
.1756267E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.2	.5306501E-01

SOLUTION VECTOR
.1681936E+00
.1626484E+00
.2572067E+00

particle size groups started at an altitude of 16000 meters and a like set of groups started at an altitude of 16000 meters plus or minus 500 meters, the mass per vertical meter for each set of groups is in the same ratio at any given sample altitude, at any given time.

The third input parameter to be studied is the total mass of material lofted by the weapon. For each of the numerical experiments in this study, the empirical value of one-third of a ton of material lofted per ton of yield is used. However, the total amount of mass lofted makes no difference in the outcome of these calculations. This is intuitively obvious from Equations (12), (13), (14), and (15). Mathematically, the total mass lofted, M_t, is only a scalar constant that is multiplied times the "F" matrix in Equation (15) and has no effect on the determination of the solution vector elements other than to increase or decrease them by the same amount.

The fourth input parameter to be varied is the mass on the filter samples. As stated earlier, the integral model assumes that all samples were taken under a set of standard sampling conditions. These conditions include, a flight path through the geometric center of the cloud at every sample altitude, and an equal amount of airflow through the filter sampling device at all sampling altitudes. Since the nuclear cloud is assumed to be normally distributed in the horizontal direction as well as in the

vertical direction, any sample technique other than a single flight through the geometric center of the cloud will require a correction factor to correct the sample mass to the standard sampling conditions.

In order to study the effect of nonstandard sampling conditions such as cloud edge sampling or multiple flights through the cloud at the same altitude with the same filter, the base case sample mass data is altered in the following two ways. First the effect of one nonstandard filter sample is studied by decreasing one of the sample masses by 3 percent of its true value and running this data through SEARCH4. Then, the same sample is increased by 10 percent of its true value and again run through SEARCH4. The resultant distribution parameters and solution vectors are listed in Tables X and XI.

The results in Table X indicate that a 3 percent error in one of the sample masses makes very little difference in the optimum particle size distribution that the SEARCH4 program selects. Moreover, the data in Table XI clearly indicates that as much as 10 percent error in one of the filter sample masses has only minor impact on the optimum particle size distribution selected by SEARCH4. The program continues to select an optimum particle size distribution that is lognormal with a log-slope between 3.7 and 4.0, and a median radius between 0.3 and 0.5 micrometers.

TABLE X

RESULTS FROM VARIATION OF ONE SAMPLE MASS DOWN 3 PERCENT FROM 41126 TO 39892

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	3.7	.8829385E-01

SOLUTION VECTOR
.1539860E+00
.1656102E-01
.1813110E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	3.9	.7847556E-01

SOLUTION VECTOR
.1388279E+00
.2916525E-01
.1812376E+00

TABLE XI

RESULTS FROM VARIATION OF ONE SAMPLE MASS
UP 10 PERCENT FROM 41126 TO 45239

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	3.7	.3525377E+00

SOLUTION VECTOR
.2548912E+00
.9350324E-02
.7045112E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	4.0	.6636146E+00

SOLUTION VECTOR
.2424191E+00
.4390633E-01
.1279647E+01

For the next part of the mass sensitivity analysis, two of the sample masses are increased by 10 percent of their true values. Table XII contains the results of this analysis. It is clear that if two sample masses are inaccurate by 10 percent in the same direction, the resultant solution vector is radically changed to include one element that is five or six order of magnitude above the other two solution vector elements. However, it is most important to note that the optimum distribution selected by SEARCH4 remains relatively unchanged with a log-slope between 3.7 and 4.0, and a median radius between 0.5 and 0.9 micrometers.

The final mass experiment involves varying one of the sample masses by plus 10 percent of its true value, and varying a second sample mass by minus 10 percent of its true value. When this is done, no good solution is found by SEARCH4. Therefore, it is clearly evident that relatively small inaccuracies in the input sample masses can greatly influence the integral model output. This extreme sensitivity to individual sample mass differences is understandable since the whole basis for the optimum distribution selection in the integral model is that the total mass on the filter is equal to the sum of the masses contributed by the equal mass groups being used to represent the falling nuclear cloud. Therefore, if the total mass on the filter is not accurately acquired, the sum of

TABLE XII

RESULTS FROM VARIATION OF TWO SAMPLE MASSES--
SAMPLE #1: UP 10 PERCENT FROM 41126 to 45239;
SAMPLE #2: UP 10 PERCENT FROM 47636 to 52400

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.9	3.7	.8085626E+05

SOLUTION VECTOR
.3046732E+00
.3029807E+00
.1400475E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.6	3.9	.6199985E+05

SOLUTION VECTOR
.2894758E+00
.3877780E+00
.1073872E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	4.0	.1043492E+06

SOLUTION VECTOR
.2873398E+00
.4305222E+00
.1807384E+06

the mass group contributions, calculated by SEARCH4, will be considerably different from the total sample mass and no optimum distribution will be found.

The fifth input parameter to be varied is the sample time of collection. In the first experiment, one sample time is varied by minus 10 percent of its true value. Next, two sample times are varied by minus 10 percent of their true values. The resultant SEARCH4 output is contained in Tables XIII and XIV. It is apparent that small inaccuracies in the sample times of collection make little impact on the SEARCH4 program output. This is especially true at late times when most of the larger particles have fallen from the cloud and only the slowly falling smaller particles are still airborne.

The final input parameter to be varied is the sample altitude. First, one sample altitude is increased by 5 percent of its original value. Second, two sample altitudes are increased by 5 percent of their original values. The results of this experiment are contained in Tables XV and XVI.

The Table XV data indicates that one sample altitude error of 5 percent or less does not significantly affect the program output. However, from the data in Table XVI, it is evident that if two sample altitudes are in error by as little as 5 percent, the program output is distinctly altered. One of the solution vector elements

TABLE XIII

RESULTS FROM VARIATION OF ONE SAMPLE TIME
DOWN 10 PERCENT FROM 182 TO 164

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	3.6	.3232540E-01

SOLUTION VECTOR
.1992990E+00
.1520953E+00
.1374395E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	3.8	.3076463E-01

SOLUTION VECTOR
.1564878E+00
.1750403E+00
.1149581E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.0	.3042188E-01

SOLUTION VECTOR
.1466314E+00
.1829093E+00
.1224689E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.11	4.3	.3597496E-01

SOLUTION VECTOR
.1318845E+00
.1947588E+00
.1330278E+00

TABLE XIV

RESULTS FROM VARIATION OF TWO SAMPLE TIMES--
SAMPLE #1: DOWN 10 PERCENT FROM 182 TO 164;
SAMPLE #2: DOWN 10 PERCENT FROM 152 TO 137

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	3.8	.2269939E+00

SOLUTION VECTOR
.2344335E+00
.5204663E-01
.5032817E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.0	.2335432E+00

SOLUTION VECTOR
.2313492E+00
.5556365E-01
.5182256E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.11	4.3	.2443441E+00

SOLUTION VECTOR
.2260754E+00
.6164088E-01
.5423967E+00

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.09	4.4	.2411485E+00

SOLUTION VECTOR
.2245084E+00
.6268384E-01
.5370646E+00

TABLE XV

RESULTS FROM VARIATION OF ONE SAMPLE ALTITUDE
UP 5 PERCENT FROM 13100 TO 13755

BASE CASE SAMPLE DATA

SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.3	3.8	.7183170E+00

SOLUTION VECTOR
.2572775E+00
.1056209E-01
.1359598E+01

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	4.0	.6974788E+00

SOLUTION VECTOR
.2501462E+00
.2239275E-01
.1328128E+01

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.11	4.3	.6921787E+00

SOLUTION VECTOR
.2406420E+00
.3673403E-01
.1324500E+01

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.09	4.4	.6669652E+00

SOLUTION VECTOR
.2381173E+00
.3973870E-01
.1281299E+01

TABLE XVI

RESULTS FROM VARIATION OF TWO SAMPLE ALTITUDES--
SAMPLE #1: UP 5 PERCENT FROM 13100 TO 13755;
SAMPLE #2: UP 5 PERCENT FROM 15800 TO 16590

BASE CASE SAMPLE DATA		
SAMPLE #1: MASS = 41126	ALTITUDE = 13100	TIME = 182
SAMPLE #2: MASS = 47636	ALTITUDE = 15800	TIME = 152
SAMPLE #3: MASS = 42575	ALTITUDE = 16200	TIME = 184

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	3.8	.1912612E+06

SOLUTION VECTOR
.2702619E+00
.2028975E+00
.3312743E+06

is increased by six orders of magnitude. Nonetheless, it is important to note that the SEARCH4 program continues to select an optimum particle size distribution with log-slope between 3.8 and 4.4, and median radius between 0.1 and 0.5 micrometers.

In summary, a sensitivity analysis of the integral model program, SEARCH4, was conducted in the following manner. The input parameters that were most likely to be in error in an actual nuclear cloud sampling scenario were varied, one at a time, in order that the effect on the program output be evaluated. Overall, this analysis indicated that the integral model program is extremely sensitive to errors in the airborne sample mass collection procedure and to sample altitude errors. If corrections are

not made for nonstandard sampling procedures, or if some of the sample altitudes are not accurate, the program does not definitively pinpoint the median radius of the stabilized cloud particle size distribution. However, it is important to note that in all cases, SEARCH4 does not fail to indicate the true log-slope of the stabilized nuclear cloud particle distribution.

This chapter presented the results of the integral model testing and evaluation, given hypothetical airborne filter sample data of known origin. It demonstrated that the integral model of airborne filter sample data analysis is a viable method for unfolding the stabilized nuclear cloud particle size distribution from the total mass collected on airborne filters. The next chapter presents a study of actual airborne filter sample data from a nuclear shot in the Pacific test range. Much of the analysis contained in this chapter will apply to the study conducted in the following chapter.

IV. Shot ZUNI Filter Sample Data Analysis

Background

Actual airborne sample data from United States atmospheric nuclear test shots conducted during the 1950s and early 1960s is not easy to find. One reason for the scarcity of data is that only a small number of test shot nuclear clouds were sampled by aircraft. In most cases, an extensive study was made of the fallout particulate material and radiation exposure rates on the ground down wind from the nuclear detonation, but cloud samples at different altitudes were seldom taken. Another reason for the difficulty in obtaining airborne sample data is that little research requiring nuclear cloud sample data has been done since Nathans published his work in 1970 (19:360-371). Consequently, most of what little data exists is probably contained in the classified archives at the national laboratories and has been virtually forgotten. In most cases, the type of data that is required by this study is not classified. Such is the case for the shot ZUNI nuclear cloud sample data cited in this chapter.

Nathans listed four nuclear test shots that were sampled by aircraft and rockets. These shots were Castle-BRAVO (1954), Redwing-ZUNI (1956), Castle-KOON (1954), and Operation Sunbeam-JOHNNY BOY (1962) (19:362). However,

the search for information on these four shots yielded only a small amount of airborne sample data from ZUNI. In the first part of this chapter, the ZUNI airborne sample data is presented along with the results of the SEARCH4 computer analysis of this data. The second part of the chapter is devoted to an analysis of the results of the SEARCH4 output and a hypothesized particle size distribution for the ZUNI stabilized cloud based on those results.

ZUNI Airborne Sample Data and SEARCH4 Results

The ZUNI airborne sample data is contained in Table XVII (Ref 5). There are some unknown facts concerning the actual method used for this sampling that lead to uncertainties in the input parameters. First of all, this data was not extracted from airborne filter samples. Rather, it is believed to have been gathered by three gas sampling devices, each mounted on a different B-57B aircraft. Second, aside from the sample altitude, the actual flight paths of the aircraft with respect to the cloud are unknown. For example, it is not known if the aircraft flew through the geometric center of the cloud at all altitudes or if the aircraft sampled only the cloud edges. Additionally, the times of collection suggest that different amounts of gas were collected at each altitude. Finally, the accuracy of the total mass per sample is suspect since it is rounded to the nearest whole number. All of these

TABLE XVII

REDWING SERIES, SHOT ZUNI AIRBORNE SAMPLE DATA

Flight	Sample Altitude (ft/m)	Sample Collection Time (min)	Sample Total Mass (oz)
TIGER RED 2	43000/13106	171-193 (182)*	9
HOTSHOT 2	51700/15758	138-165 (151.5)*	11
KASSADY 1	53300/16246	169-199 (184)*	5

* Note: Mean sample time of collection.

uncertainties greatly enhance the potential for the existence of nonstandard sampling conditions like those presented in Chapter III. But, since this is the only actual nuclear cloud sample data that was uncovered during the data search, it constitutes the best available data and merits a complete analysis.

In order to properly analyze the ZUNI data and better interpret the analytical results, some additional background information for the shot is necessary. The device was detonated on a platform at a height of 9 feet over coral soil at the Bikini atoll on 28 May 1956 at 0556 hours. It produced a yield of 3.5 megatons. The nuclear cloud stabilized in approximately 5 minutes. Its top reached an altitude of 79000 feet (24100 meters) and its bottom stabilized at approximately 49000 feet (14900 meters). At one hour following the detonation, the

tropopause was at an altitude of 51000 feet (15500 meters) (10:111,114). Figure 3 graphically portrays the ZUNI cloud sampling scenario and brings into perspective the sample locations relative to the nuclear cloud position at sampling time.

The ZUNI airborne sample data contained in Table XVIII was input to the SEARCH4 program. For the first run, only three equal mass groups were used for the calculations. The results from this run are contained in Table XIX. Additional SEARCH4 runs were made with four through eight equal mass groups. The results from these additional runs are contained in Tables XX through XXIV.

One change is made in order to accommodate the difference in total mass per vertical meter at the sampling altitudes versus the very small fraction of that total mass collected by the sampling devices. This change is necessary to produce solution vectors that are directly comparable to the ones in the Chapter III sensitivity analysis. In that sensitivity analysis, the input sample masses represented the total mass per vertical meter at the sampling altitudes. The ZUNI samples, listed in Table XVIII, represent only a very small fraction of the total mass per vertical meter at the sampling altitudes. In fact, they are five orders of magnitude less than the samples created for the Chapter III model validation study (listed in Table II). As determined during the model

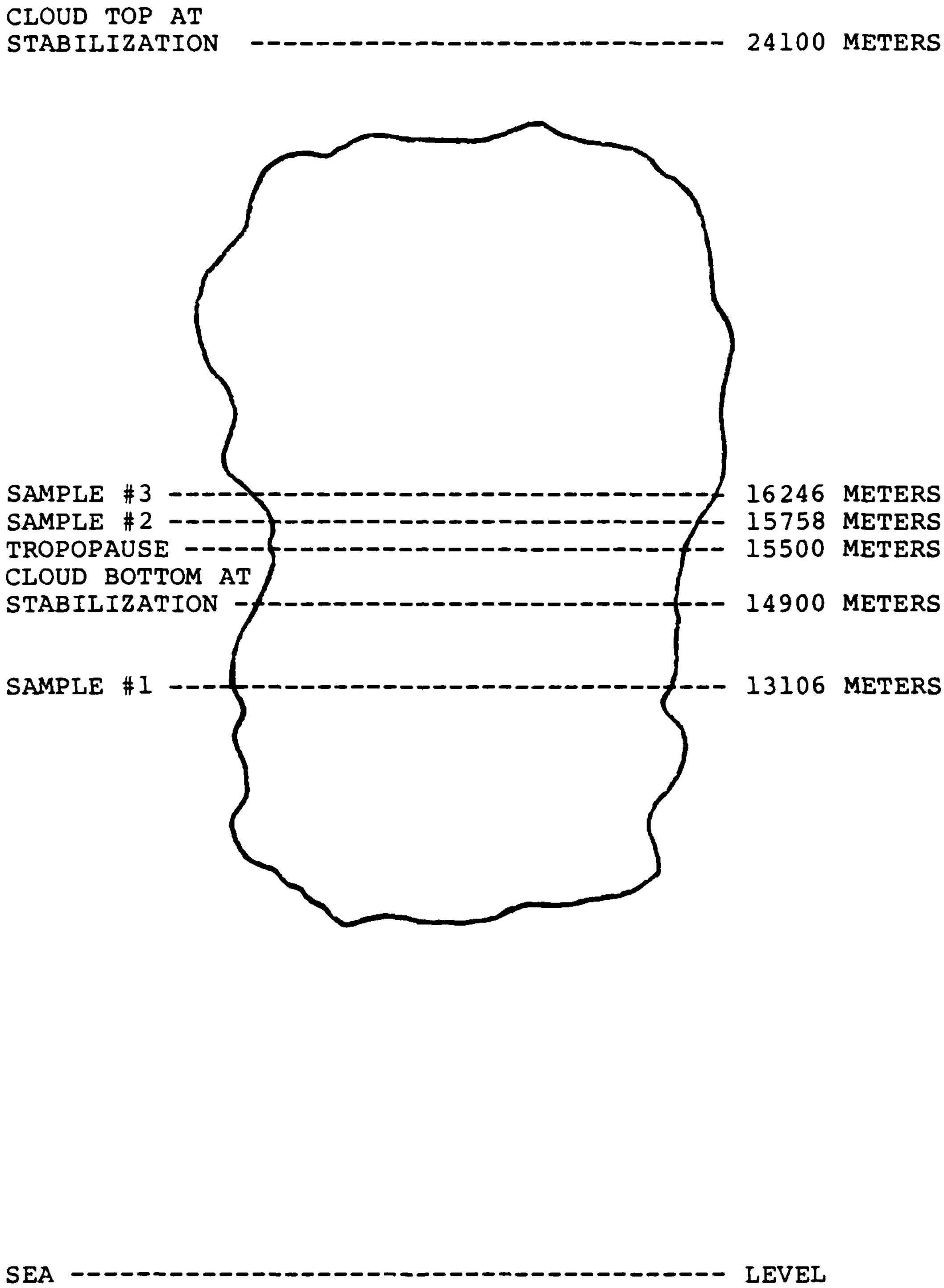

Fig. 3. Redwing Series, Shot ZUNI Nuclear Cloud

TABLE XVIII

INPUT DATA FILE "FILTER" FOR ZUNI SAMPLE ANALYSIS

YIELD = 3500 (kt) NUMBER OF SAMPLES = 3
DISTRIBUTION MOMENT = 3 MASS ALOFT = 1.06×10^4 (kg)

	(kg)	(m)	(min)
SAMPLE #1:	MASS = .255	ALTITUDE = 13106	TIME = 182.0
SAMPLE #2:	MASS = .3118	ALTUTUDE = 15758	TIME = 151.5
SAMPLE #3:	MASS = .142	ALTUTUDE = 16246	TIME = 184.0

TABLE XIX

RESULTS OF ZUNI DATA SEARCH USING THREE EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
1.0	2.9	.9479308E+06

SOLUTION VECTOR
.3316389E-01
.1456210E+00
.1641864E+07

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.05	4.8	.1725676E+06

SOLUTION VECTOR
.9411089E-01
.2988994E+06
.7072789E+01

TABLE XX

RESULTS OF ZUNI DATA SEARCH USING
FOUR EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION	SOLUTION VECTOR
5.0	2.5	.6225378E+06	.1043578E+00 .4235624E+00 .1078267E+07
4.0	2.6	.9036186E+06	.9877644E-01 .4135901E+00 .1565114E+07
3.0	2.7	.1281178E+06	.8797728E-01 .2724262E+00 .2219067E+06
1.0	3.2	.8869613E+06	.7862210E-01 .2335695E+00 .1536262E+07

TABLE XX--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	3.5	.4926050E+06

SOLUTION VECTOR
.7075585E-01
.1847197E+00
.8532169E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.2	3.9	.1439821E+06

SOLUTION VECTOR
.5647343E-01
.1530068E+00
.2493845E+06

TABLE XXI

RESULTS OF ZUNI DATA SEARCH USING
FIVE EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION	SOLUTION VECTOR
8.0	2.4	.1323250E+06	.1451400E+00 .2569704E+00 .2291939E+06
0.06	4.7	.1111025E+06	.6348051E-01 .1655484E+00 .1924353E+06
0.05	4.8	.1753679E+06	.6393483E-01 .1671012E+00 .3037462E+06
0.035	5.0	.5701899E+06	.6536677E-01 .1719004E+00 .9875980E+06

TABLE XXII

RESULTS OF ZUNI DATA SEARCH USING
SIX EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION	SOLUTION VECTOR
1.5	3.3	.9389467E+06	.1006949E+00 .7017220E+00 .1626304E+07
0.5	3.8	.1213967E+06	.8438121E-01 .3214669E+00 .2102655E+06
0.07	4.8	.2197830E+06	.7509261E-01 .2227036E+00 .3806755E+06
0.06	4.9	.8750562E+06	.7737525E-01 .2541977E+00 .1515642E+07
0.047	5.0	.1244411E+06	.7155147E-01 .1963516E+00 .2155385E+06

TABLE XXIII

RESULTS OF ZUNI DATA SEARCH USING
SEVEN EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
5.0	2.8	.4525707E+06

SOLUTION VECTOR
.1549908E+00
.1833116E+00
.7838756E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
4.0	2.9	.2655316E+06

SOLUTION VECTOR
.1356493E+00
.5953607E+00
.4599146E+06

TABLE XXIV

RESULTS OF ZUNI DATA SEARCH USING
EIGHT EQUAL MASS GROUPS

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
3.0	3.1	.1786807E+06

SOLUTION VECTOR
.1293275E+00
.6663778E+00
.3094845E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
2.0	3.3	.1856012E+06

SOLUTION VECTOR
.1151535E+00
.7367282E+00
.3214711E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
1.1	3.6	.2304726E+06

SOLUTION VECTOR
.1030899E+00
.6933915E+00
.3991906E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.9	3.7	.2225878E+06

SOLUTION VECTOR
.9987001E-01
.6500016E+00
.3855338E+06

TABLE XXIV--Continued

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.6	3.9	.1585163E+06

SOLUTION VECTOR
.9413213E-01
.5345019E+00
.2745585E+06

MEDIAN RADIUS (um)	BETA	STANDARD DEVIATION
0.5	4.0	.2620418E+06

SOLUTION VECTOR
.9349972E-01
.5644583E+00
.4538701E+06

sensitivity analysis, the total mass of material lofted by the weapon has no effect on the optimum particle size distribution that the SEARCH4 program selects. However, it does affect each of the solution vector elements by the same amount. Therefore, in order to make the ZUNI output solution vectors directly comparable to the solution vectors in the model sensitivity study, rather than increasing each sample mass by the same amount, the total mass lofted was decreased by five orders of magnitude. This change does produce solution vectors that are directly comparable to the ones in the sensitivity analysis section of Chapter III. Moreover, it does not affect the optimum particle size distribution selected by the SEARCH4 program.

Analysis of ZUNI Airborne Sample Search Results

Initially, the results of the ZUNI search contained in Tables XIX through XXIV appear to be inconclusive. In all cases, for the optimum particle size distribution selected by the SEARCH4 program, the accompanying solution vector has two elements that are within one order of magnitude of each other and a third element that is six orders of magnitude larger than the first two. An acceptable solution vector would be one with all of its elements equal, or at least, same order of magnitude. Without any further knowledge of the program's sensitivity to certain

input, the output contained in Tables XIX through XXIV does not indicate an acceptable solution.

However, in light of the SEARCH4 program sensitivity analysis conducted in Chapter III, it is possible that the results of the ZUNI search can be interpreted. It was discovered during the sample mass portion of the sensitivity analysis that if two of the sample masses were in error by as little as 10 percent, the resultant program output solution vector would contain two elements that were the same order of magnitude, and one element that was about six orders of magnitude larger than the other two. Yet, even though the solution vector was unacceptable, the log-slope of the optimum particle size distribution, selected by the SEARCH4 program was surprisingly close to, if not identical to the actual log-slope used to construct the input sample mass data.

Since little is known about the sampling conditions for this ZUNI sample data other than sample altitude and time of collection, it is most likely that these samples were not taken in accordance with the standard sampling conditions assumed by the SEARCH4 program. For example, the sampling aircraft probably did not fly through the cloud center at each sampling altitude. Additionally, each total sample collection time is longer than the time that it would have taken the aircraft to fly through the cloud once. This could indicate multiple passes at each altitude.

These differences could easily account for a 10 percent variation in the sample masses.

The resultant hypothesis is that because of non-standard sampling methods, two of these ZUNI airborne samples are 10 percent greater than what they should have been. If this is true, then the lesson learned in the program sensitivity analysis in Chapter III can be applied. That is, even though the solution vector is unacceptable, the optimum particle size distribution log-slope selected by the SEARCH4 program may indicate the true log-slope of the stabilized nuclear cloud particle size distribution.

In this case, the optimum log-slope selected by the SEARCH4 program varies from 2.7 to 5.0 depending on how many equal mass groups are used for the analysis. For the ZUNI analysis, dividing the mass aloft into eight equal mass groups and then using only the first three groups assumes that 63 percent ((1/8)*5) of the mass lofted by the weapon has fallen below the sampling altitudes during the three hours prior to sampling. This assumption is probably not completely valid, but serves as a limiting case. Regardless of how many groups were used for the analysis, the SEARCH4 program most frequently selected log-slopes that were between 2.9 and 3.9. However, this is by no means a clear indication of the actual particle size distribution log-slope. Perhaps all that can be said at this point is that the integral method of airborne

sample analysis for the shot ZUNI samples indicates that the log-slope for the particle size distribution of the ZUNI stabilized nuclear cloud may be between 2.9 and 3.9 but is definitely not less than 2.7 nor greater than 5.0.

The next chapter proposes an alternative method for analyzing sample data. This method uses the relative number of particles of each size, found on the filter to unfold the stabilized nuclear cloud particle size distribution and is therefore called the differential method. It is hoped that both the integral and the differential methods can be used together for the same set of filter samples to better pinpoint the actual nuclear cloud particle size distribution.

V. The Differential Method

Background

One benefit of using the integral method of airborne filter sample analysis is that, aside from the sample altitude, time of collection, and aircraft flight path information, the total mass on each sample is the only other piece of data that is required. No information concerning the particle sizes found in the samples is needed. Based on Colarco's (6:67) particle fall time versus radius data, good assumptions concerning the particle sizes that should be found in the samples can be made. However, as demonstrated in Chapter IV, the integral method solutions may not be conclusive. Consequently, the theory for an alternative method, the differential method, has been developed.

This differential method uses the relative number of particles of each size found in the airborne sample in conjunction with the sample altitude, time of collection, and aircraft flight path information to unfold the stabilized nuclear cloud particle size distribution. Reduced airborne sample data from actual nuclear clouds containing the relative number of particles of each size on each sample was not available when this study was completed. Hopefully, such data will be available for a future study. In

anticipation of this, the differential method theory is presented in this chapter.

Differential Method Theory

Essentially, the differential method uses the same particle fall mechanics and initial stabilized cloud model as presented in Chapter II. The major difference is that an assumed particle mass-size distribution is not used. Rather, an assumed particle number-size distribution is used to calculate the number of particles, of each size found in the airborne sample, that would have been present at cloud stabilization had the assumed particle size distribution represented the nuclear cloud at stabilization. Then, each of these groups is represented by a vertical gaussian and allowed to fall from its initial lofted altitude for a time equal to the sample collection time. Finally, the number of particles in each size group at the sample altitude is compared to the number of particles of that same size found on the sample. In other words, a ratio is made of the calculated number of particles of a given size at a given altitude to the measured number of particles in an airborne sample of that same size at that same altitude. If all of these ratios for all the groups are equal or close to equal, then the assumed particle size distribution is the one that must have represented the nuclear cloud at stabilization. One obvious advantage

to this method is that only one good airborne sample is required for the analysis.

The following algorithm outlines the differential method of airborne sample analysis:

1. Airborne sample data, to include sample altitude, time of collection, and relative number of particles per particle radius found on the sample are input.

2. The first assumed lognormal particle size distribution is used to calculate the number of particles in each of the measured sizes.

3. A vertical gaussian representing each of these groups is allowed to fall from its initial lofted altitude for a time equal to the sample collection time.

4. The number of particles at the sample altitude from each of these falling groups is calculated.

5. This calculated number of particles is compared to the measured number of particles in the airborne sample in ratio.

6. All the ratios from all the different size groups are compared to each other and a standard deviation from an algebraic mean for these ratios is calculated.

7. Another trial distribution is selected and the process is begun again. The trial distribution that produces the smallest standard deviation among the group ratios is the particle size distribution that best represents the stabilized nuclear cloud.

This differential method of airborne sample analysis may seem simpler than the integral method since it requires only one sample. However, there are some limitations to this method. For example, there is considerable difficulty involved in obtaining an accurate breakdown of the relative number of particles of each size on an airborne sample (15:21). Additionally, the same corrections for nonstandard sampling conditions that applied to the integral method apply to the differential method as well. Moreover, rather than base conclusions about the nature of a nuclear cloud particle size distribution on the results of one sample analysis, it is recommended that the integral method of airborne sample analysis be used in conjunction with the differential method. Then the results from both methods of analysis can be used to predict the stabilized nuclear cloud particle size distribution.

VI. Conclusions and Recommendations

Conclusions

In order to accurately predict fallout patterns, the nuclear cloud particle size distribution must be known. However, analysis of fallen material alone may lead to inaccurate conclusions concerning the particle size distribution in the nuclear cloud. For example, in Hopkins' analysis of the Mt. St. Helens ash cloud he discovered that because of breakage on impact and sieving of the fallen material, the particle size distribution calculated from the fallen material analysis could not be used to model the observed fallout pattern (17:86). Likewise, for nuclear clouds, analysis of fallen material alone may be misleading. Therefore, the best estimate of the actual falling particle size distribution in a nuclear cloud can be made from analysis of fallen material samples as well as analysis of cloud samples taken at different altitudes and different times. This study presented two methods for unfolding the nuclear cloud particle size distribution from nuclear cloud sample analysis.

The integral method of nuclear cloud sample analysis presented in Chapter II is a viable method of unfolding the stabilized nuclear cloud particle distribution if the sampling conditions were well documented. If not, this

method produces results that are inconclusive. The major advantage of the integral method is that, aside from the standard information concerning where and when the samples were taken with respect to the nuclear cloud location, the only other sample data required is the total mass on each of the filter samples. Additionally, if total activity on each of the filter samples at a given time after the burst is known, the integral method of activity summation rather than mass summation can be used to unfold the stabilized nuclear cloud particle distribution if some additional assumptions are made. These assumptions are incorporated into the code by minor modifications that include using Freiling's 2.5 moment approximation (12:6) for the activity distribution versus particle size, and the Way-Wigner (23:1318) approximation for fission product decay.

If a more detailed reduction of sample data, including the relative number of particles of each size on each of the filter samples is available, the differential method of nuclear cloud sample analysis presented in Chapter IV can be used to unfold the nuclear cloud particle size distribution. Unlike the integral method, the differential method does not require as much information concerning the actual sampling conditions, aside from sample altitude and sample time of collection. For example, since particles of all sizes in a nuclear cloud are assumed to be normally distributed in the horizontal plane, the

details on the cloud penetration other than altitude of penetration are not important. Only the relative number of particles per radius is important and this will not vary with different aircraft penetration points at any given altitude. However, the tradeoff is that the more detailed sample data reduction for the early U.S. atmospheric tests is difficult to acquire.

The optimum approach to unfolding the nuclear cloud particle size distribution from airborne cloud samples is to acquire a set of filter sample data that will allow the use of both the integral and differential methods presented in this study. Obviously, if enough data is available for a given nuclear cloud to allow the use of both of these methods, then the cloud particle size distribution can be predicted with greater certainty.

Recommendations

There are three recommendations to be made. The first one is that a thorough search be made of the classified archives at each of the national laboratories, Lawrence Livermore and Los Alamos, for reduced cloud sample data. Both labs were sponsors for the atmospheric tests and there is a high probability that sufficiently reduced sample data already exists in their archives. In most cases, the type of data required by the two methods presented in this study is unclassified. Such was the case for the ZUNI data used in Chapter IV.

The remaining two recommendations concern modifications to the code contained in Appendix B. A better method should be developed for conducting the search rather than trial and error. Also, the code should be modified to accept the required data and perform both integral and differential analysis of airborne samples. These modifications, along with a set of sampling standards could be used to facilitate the analysis of data from any future sampling endeavors.

Appendix A: Empirical Cloud Loft Model

This appendix contains the empirical equations used to spatially position the stabilized nuclear cloud. Two sets of equations are used. The first set was developed by Hopkins using a polynomial least squares fit from DELFIC output for various yields. With weapon yield in kilotons and particle radius in micrometers as input, these equations can be used to calculate the altitude of a vertical gaussian representing any mono-size group of particles at cloud stabilization time (16:14-15):

$$H_g = (\mathrm{SLOPE} * 2 * R) + (\mathrm{INTERCEPT})$$

$$\mathrm{SLOPE} = -\ \mathrm{EXP}\{1.574 - 0.01197*\ln(\mathrm{YKT}) + 0.03636*\ln(\mathrm{YKT})^2 - 0.0041*\ln(\mathrm{YKT})^3 + 0.0001965*\ln(\mathrm{YKT})^4\}$$

$$\mathrm{INTERCEPT} = \mathrm{EXP}\{7.889 + 0.34*\ln(\mathrm{YKT}) + 0.001226*\ln(\mathrm{YKT})^2 - 0.005227*\ln(\mathrm{YKT})^3 + 0.000417*\ln(\mathrm{YKT})^4\}$$

where

H_g = the average lofted altitude, in meters, of the center of a vertical gaussian representing a mono-size group of particles of radius R

R = the radius in micrometers of particles in the mono-size group

YKT = the weapon yield in kilotons

The next set of empirical equations were developed by Conners using methods similar to those used by Hopkins, above. These equations are used to calculate the standard deviation for each of the mono-size group vertical gaussian distributions (7:19-20):

$$Z_g = (\text{SLOPE} * 2 * R) + (\text{INTERCEPT})$$

$$\text{SLOPE} = 7 - \text{EXP}\{1.78999 - 0.048249*\ln(\text{YKT}) + 0.0230248*\ln(\text{YKT})^2 - 0.00225965*\ln(\text{YKT})^3 + 0.000161519*\ln(\text{YKT})^4\}$$

$$\text{INTERCEPT} = \text{EXP}\{7.03518 + 0.158914*\ln(\text{YKT}) + 0.0837539*\ln(\text{YKT})^2 - 0.0155464*\ln(\text{YKT})^3 + 0.000862103*\ln(\text{YKT})^4\}$$

where

Z_g = the predicted vertical thickness in meters of a mono-sized group of particles with radius R

R = the radius in micrometers of particles in the mono-size group

YKT = the weapon yield in kilotons

If Z_g is assumed to be a two-sigma distribution, then the standard deviation, in meters, for each mono-size group vertical gaussian is defined:

$$\sigma_g = 0.25 * Z_g$$

Appendix B: SEARCH4 Computer Code and Glossary of Program Variables

This appendix contains the computer code that employs the integral method of airborne filter sample analysis. It is written in FORTRAN-5 (FORTRAN-77) and was run on a CYBER 170-845. Following the code listing are example input files, FILTER and SEARCH, and a glossary of all the variables used in the program.

```
***********************    SEARCH4    ***********************
**           FORTRAN-77  (FORTRAN-5) ON CYBER              **
**                                                         **
**   13 NOVEMBER 1985 ** A FORTRAN VERSION OF FILTER4C     **
**  (BASIC PROGRAM) THAT SEARCHES FROM BETA=2 to BETA=5    **
**     FOR AN APPROPRIATE SOLUTION VECTOR.  PARTICLE       **
**     SIZE RANGE ON THE FILTER SAMPLES IS FROM A FEW      **
**              MICRONS TO 70-120 MICRONS.                 **
**         INPUT: FROM FILES "FILTER" AND"SEARCH"          **
**               ALSO, TWO INTERACTIVE QUESTIONS.          **
**         OUTPUT: TO A FILE "ANSWER"                      **
**                                                         **
*************************************************************
** TYPE STATEMENTS **
      PROGRAM START
      REAL INMASS(25), ZZERO(25), R(25), SIGMA(25), TOTMAS(25)
```

```
      REAL TAME(25), ALTCHK(25), A(25,25), B(25,50), C(25)
      REAL RHOF, YKT, MASS, TONE, BETA, ALPHA1, ISTEP, G
      REAL ALPHA2, NUMGRP, MOMENT, RAT, BP, PDINC, PDCHK
      REAL Z, PD, RIGHT, LEFT, HOLT, RHO, AIDA, TEMPAL, R2CD
      REAL REY, VZ, SLPDRG, DELTAT, ALTZ, DZ, DUMMY, SUMMER
      REAL DTHOLD, GAUSS, BF, TEMP, TOTAL, DENOM
      REAL YOU, WIN, CRAB, AVERAG, FISH, PIG
      REAL EXTRAS
      INTEGER PLUTO, I, MARK, COLT, FLAG, J, T, FIGS, OMEGA
      INTEGER M, K, N, Q, P, H, F, U, X, Y, MINUSE, QUICK
      INTEGER ZETA
** INITIALIZATION **
      RHOF = 2600.0
      G = 9.77
      MARK = 0
      RIGHT = 0
      LEFT = 0
      FLAG = 0
      PDCHK = 0
      COLT = 0
      FIGS = 0
      HOLT = 0
      SUMMER = 0
      CRAB = 0
      MINUSE = 0
      FISH = 0
```

```
      OMEGA = 0
      ZETA = 0
** READ FILTER DATA INPUT FILE **
      OPEN(UNIT=7,FILE='FILTER')
      REWIND 7
      READ(7,107) YKT
      PRINT*, 'YKT = ',YKT
      READ(7,111) PLUTO
      PRINT*, 'NUMBER OF SAMPLES = ',PLUTO
 111  FORMAT(I6)
      READ(7,107) MOMENT
      PRINT*, 'DISTRIBUTION MOMENT = ',MOMENT
 107  FORMAT(F6.0)
      READ(7,108) MASS
      PRINT*, 'MASS ALOFT = ',MASS
 108  FORMAT(E13.2)
      DO 10 I = 1, PLUTO
      READ(7,109) TOTMAS(I),ALTCHK(I),TONE
      PRINT*, 'SAMPLE NUMBER ',I,' :   MASS = ',TOTMAS(I),'
     $ALTITUDE = ',ALTCHK(I),'   TIME = ',TONE
 109  FORMAT(F9.0,F5.0,F5.1)
      TAME(I) = TONE*60.0
 10   CONTINUE
      OPEN(UNIT=6,FILE='SEARCH')
      REWIND 6
      READ(6,349) BETA,ALPHA1,ALPHA2,ISTEP,NUMGRP
```

```
 349  FORMAT(F4.1,F6.1,F7.2,F5.1,F5.1)
** INTEROGATE HUMAN FOR INPUT **
      PRINT*, ' '
      PRINT*, 'DO YOU WANT A QUICK SEARCH ?'
      PRINT*, '(ENTER 1 FOR QUICK SEARCH)'
      READ*, QUICK
      IF (QUICK .EQ. 1) THEN
           DENOM = 1.0
      ELSE
           DENOM = 10.0
      END IF
      ISTEP = ISTEP/DENOM
      PRINT*, ' '
      PRINT*, 'DO YOU WANT TO USE MORE EQUAL MASS GROUPS ?'
      PRINT*, 'IF SO, ENTER THE NUMBER TO BE ADDED TO NUMGRP.'
      PRINT*, 'IF NOT, ENTER 0.'
      READ*, EXTRAS
      NUMGRP = NUMGRP + EXTRAS
      PRINT*, ' '
      PRINT*, 'ENTER THE OUTPUT PARAMETER.'
      PRINT*, '(ENTER 1 FOR SOLUTION VECTORS WITH MINUSES <= 1)'
      PRINT*, '(ENTER 0 FOR SOLUTION VECTORS WITH MINUSES  = 0)'
      READ*, ZETA
      IF (ZETA .NE. 1) THEN
           ZETA = 0
      END IF
```

```
** END OF INPUT **
      PRINT*,'           CURRENTLY WORKING ON BETA = ',BETA
** OPEN OUTPUT FILE AND WRITE HEADINGS **
      OPEN(8,FILE='ANSWER',STATUS='NEW')
 101  FORMAT(' ')
** GOSUB FOR PARTICLE DISTRIBUTION CALCULATION **
 1    CONTINUE
      DO 15 I = 1, PLUTO
      CALL PARTY(R(I),BETA,ALPHA1,NUMGRP,MOMENT,ISTEP,
     $ALPHA2,COLT,PLUTO,FLAG,PDCHK,OMEGA,DENOM,EXTRAS)
      IF (OMEGA .EQ. 1) THEN
          GO TO 35
      END IF
 15   CONTINUE
      DO 20 I = 1, PLUTO
      INMASS(I) = MASS/NUMGRP
 20   CONTINUE
** GOSUB FOR GROUP LOFTED ALTITUDE AND SIGMA CALCULATION **
      DO 30 I = 1,PLUTO
      CALL HOPKIN(R(I),ZZERO(I),SIGMA(I),YKT,PLUTO)
 30   CONTINUE
** GOSUB TO USAIR WITH THE LARGEST PARTICLE'S LOFTED ALTITUDE **
      TEMPAL = ZZERO(PLUTO)-700.0
      CALL USAIR(TEMPAL,RHO,AIDA)
** CALCULATE DELTAT **
      R2CD = (32.0*RHO*RHOF*G*(R(PLUTO)**3))/(3.0*(AIDA**2))
```

```
      IF (R2CD .LT. 120.0) THEN
           REY = (R2CD/24.0)-(2.3363E-4*(R2CD**2))+(2.0154E
     $-6*(R2CD**3))-(6.9105E-9*(R2CD**4))
      ELSE
           REY = 10.0**((-1.29536)+(.986*ALOG10(R2CD))-
     $(.046677*(ALOG10(R2CD))**2)+(1.1235E-3*(ALOG10(R2CD))
     $**3))
      END IF
      VZ = (REY*AIDA)/(2.0*RHO*R(PLUTO))
      SLPDRG = 1.0+(1.165E-7/(R(PLUTO)*RHO))
      DELTAT = 1400.0/(VZ*SLPDRG)
** MAIN PROGRAM======>> PARTICLE GROUP FALL MECHANICS LOOPS
  $ <<=== **
      DO 50 J = 1,PLUTO
      DO 60 T = 1,PLUTO
      ALTZ = ZZERO(T)
36    CONTINUE
      CALL USAIR(ALTZ,RHO,AIDA)
      R2CD = (32.0*RHO*RHOF*G*(R(T)**3))/(3.0*(AIDA**2))
      IF (R2CD .LT. 120.0) THEN
           REY = (R2CD/24.0)-(2.3363E-4*(R2CD**2))+(2.0154E
     $-6*(R2CD**3))-(6.9105E-9*(R2CD**4))
      ELSE
           REY = 10.0**((-1.29536)+(.986*ALOG10(R2CD))-
     $(.046677*(ALOG10(R2CD))**2)+(1.1235E-3*(ALOG10(R2CD))
     $**3))
```

```
      END IF
      IF (ALTZ .LT. 0) THEN
           GO TO 31
      END IF
      VZ = (REY*AIDA)/(2.0*RHO*R(T))
      SLPDRG = 1.0+(1.165E-7/(R(T)*RHO))
      DZ = VZ*SLPDRG*DELTAT
 31   CONTINUE
      ALTZ = ALTZ - DZ
      DUMMY = INMASS(T)
      IF (ALTZ .LE. 0) THEN
           GAUSS = 0
           GO TO 32
      END IF
      GAUSS = (DUMMY*EXP(-.5*(((ALTCHK(J)-ALTZ)/SIGMA(T))
     $**2)))/(SQRT(2.0*3.14159)*SIGMA(T))
      SUMMER = SUMMER + DELTAT
      IF (GAUSS .LT. 1.0E-10) THEN
           GAUSS = 0
           GO TO 32
      END IF
      IF (FIGS .EQ. 1) THEN
           GO TO 34
      END IF
      IF ((SUMMER+DELTAT) .GT. TAME(J)) THEN
           FIGS = 1
```

```
          DTHOLD = DELTAT
          DELTAT = TAME(J) - SUMMER
          GO TO 36
     ELSE
          GO TO 36
     END IF
34   CONTINUE
     DELTAT = DTHOLD
     FIGS = 0
32   CONTINUE
     A(J,T) = GAUSS
     SUMMER = 0
60   CONTINUE
50   CONTINUE
** FINAL DETERMINATION OF THE A VALUES AND A VALUE COMPARISON **
** 1. INVERSION OF THE COEFFICIENT MATRIX **
     DO 61 T = 1,PLUTO
     DO 62 H = 1,PLUTO
     A(T,H) = A(T,H)*NUMGRP
62   CONTINUE
61   CONTINUE
     N = PLUTO
** SET-UP OF WORKAREA MATRIX WITH IDENTITY MATRIX ON THE RIGHT **
     DO 63 I = 1,N
     DO 64 J = 1,N
     B(I,N+J) = 0
```

```
      B(I,J) = A(I,J)
 64   CONTINUE
      B(I,I+N) = 1
 63   CONTINUE
** GAUSS-JORDIN ELIMINATION TO DETERMINE THE INVERSE **
      DO 65 K = 1,N
      IF (K .EQ. N) THEN
           GO TO 53
      END IF
      M = K
      DO 67 I = (K+1),N
      YOU = ABS(B(I,K))
      WIN = ABS(B(M,K))
      IF (YOU .GT. WIN) THEN
           M = I
      END IF
 67   CONTINUE
      IF (M .EQ. K) THEN
           GO TO 53
      END IF
      DO 68 J = K,(2*N)
      BF = B(K,J)
      B(K,J) = B(M,J)
      B(M,J) = BF
 68   CONTINUE
 53   CONTINUE
```

```
      DO 66 J = (K+1),(2*N)
      IF (B(K,K) .EQ. 0) THEN
           GO TO 89
      END IF
      B(K,J) = B(K,J)/B(K,K)
66    CONTINUE
      IF (K .EQ. 1) THEN
           GO TO 69
      END IF
      DO 70 I = 1,(K-1)
      DO 71 J = (K+1),(2*N)
      B(I,J) = B(I,J) - B(I,K)*B(K,J)
71    CONTINUE
70    CONTINUE
      IF (K .EQ. N) THEN
           GO TO 72
      END IF
69    CONTINUE
      DO 73 I = (K+1),N
      DO 74 J = (K+1),(2*N)
      B(I,J) = B(I,J) - B(I,K)*B(K,J)
74    CONTINUE
73    CONTINUE
65    CONTINUE
72    CONTINUE
** RETRIEVE THE INVERSE FROM THE RIGHT SIDE OF B **
```

```
      DO 75 I = 1,N
      DO 76 J = 1,N
      B(I,J) = B(I,J+N)
 76   CONTINUE
 75   CONTINUE
** SHIFT B TO A FOR NEXT OPERATION **
      DO 77 Q = 1,N
      DO 78 P = 1,N
      A(Q,P) = B(Q,P)
 78   CONTINUE
 77   CONTINUE
** 2. MULTIPLY A, THE INVERSE MATRIX TIMES B, THE SAMPLE VECTOR **
      M = N
      I = N
      J = 1
      TOTAL = 0
** INPUT THE RIGHT MATRIX **
      DO 79 F = 1,I
      DO 80 U = 1,J
      B(F,U) = TOTMAS(F)
 80   CONTINUE
 79   CONTINUE
      DO 81 I = 1,M
      DO 82 X = 1,J
      DO 83 Y = 1,N
      TEMP = A(I,Y)*B(Y,X)
```

```
      TOTAL = TOTAL + TEMP
      IF (Y .EQ. N) THEN
           C(I) = TOTAL
           TOTAL = 0
      END IF
 83   CONTINUE
 82   CONTINUE
 81   CONTINUE
** 3. FINALLY, A LOGNORMAL CURVE-FIT CHECK CODE **
      DO 87 I = 1,PLUTO
      CRAB = CRAB + C(I)
      IF (C(I) .LT. 0) THEN
           MINUSE = MINUSE +1
           IF (MINUSE .GT. ZETA) THEN
                GO TO 89
           END IF
      END IF
 87   CONTINUE
      PIG = PLUTO
      AVERAG = CRAB/PIG
      DO 91 I = 1,PLUTO
      FISH = FISH + (C(I)-AVERAG)**2
 91   CONTINUE
      FISH = SQRT(FISH/(PIG-1))
      IF (FISH .GT. 1000000) THEN
           GO TO 89
```

```
      END IF
      HOLT = ALPHA1-ISTEP
      WRITE(8,101)
      WRITE(8,101)
      WRITE(8,100)
100   FORMAT('      ALPHA      BETA       STANDARD DEVIATION
     $      MINUSES')
      WRITE(8,228) HOLT,BETA,FISH,MINUSE
228   FORMAT(2X,F8.5,4X,F5.1,7X,E15.7,20X,I2)
      WRITE(8,101)
      WRITE(8,555)
555   FORMAT(29X,'SOLUTION VECTOR')
      DO 93 I = 1,PLUTO
      WRITE(8,371) C(I)
371   FORMAT(22X,E18.7)
93    CONTINUE
      WRITE(8,101)
89    CONTINUE
      CRAB = 0
      FISH = 0
      AVERAG = 0
      MINUSE = 0
** GO GET ANOTHER DISTRIBUTION TO CHECK **
      GO TO 1
35    CONTINUE
      REWIND 8
      END
```

```
***************************************
**          SUBROUTINE PARTY           **
***************************************
      SUBROUTINE PARTY(ROOT,BETA,ALPHA1,NUMGRP,MOMENT,ISTEP,
     $ALPHA2,COLT,PLUTO,FLAG,PDCHK,OMEGA,DENOM,EXTRAS)
      REAL ROOT,BETA,ALPHA1,NUMGRP,MOMENT,ISTEP,ALPHA2,
     $ALPHA3,RAT,BP
      REAL R(25),PDINC,PDCHK,PD,Z,LEFT,RIGHT,DENOM
      REAL EXTRAS
      INTEGER PLUTO,FLAG,COLT,I,OMEGA
      IF (COLT .EQ. 1) THEN
           READ(6,349) BETA,ALPHA1,ALPHA2,ISTEP,NUMGRP
 349       FORMAT(F4.1,F6.1,F7.2,F5.1,F5.1)
           NUMGRP = NUMGRP + EXTRAS
           PRINT*,'          CURRENTLY WORKING ON BETA = ',BETA
           ISTEP = ISTEP/DENOM
           COLT = 0
      END IF
      IF (BETA .EQ. 0) THEN
           OMEGA = 1
           RETURN
      END IF
      RAT = 10000.0
      LEFT = 0
      RIGHT = 0
      BP = ALOG(BETA)
```

```
      ALPHA3 = ALOG(ALPHA1) + (MOMENT*BP**2)
      IF (FLAG .GT. 0) THEN
           GOTO 5
      END IF
      PDINC = (100.0/NUMGRP)/100.0
      PDCHK = PDINC/2.0
5     CONTINUE
      Z = (ALOG(RAT)-ALPHA3)/BP
      IF(Z .GE. 0) THEN
           PD=1.0-.5/(1.0+.196854*Z+.115194*Z**2+.000344*Z
     $**3+.019527*Z**4)**4
      ELSE
           Z = ABS(Z)
           PD=.5/(1.0+.196854*Z+.115194*Z**2+.000344*Z**3+
     $.019527*Z**4)**4
      END IF
      IF (PD .GT. PDCHK) THEN
           RIGHT = RAT
           RAT = (RIGHT-LEFT)/2.0 + LEFT
      ELSE
           LEFT = RAT
           RAT = (RIGHT-LEFT)/2.0 + LEFT
      END IF
      IF ((ABS(PD-PDCHK)) .LT. .00001) THEN
           PDCHK = PDCHK + PDINC
           FLAG = FLAG + 1
```

```
          ROOT = RAT * .000001
          RAT = 10000.0
          IF (FLAG .GE. PLUTO) THEN
               GOTO 6
          ELSE
               GOTO 7
          END IF
     ELSE
          GOTO 5
     END IF
 6   CONTINUE
     ALPHA1 = ALPHA1 + ISTEP
     IF (ALPHA1 .GT. ALPHA2) THEN
          COLT = 1
     END IF
     FLAG = 0
 7   CONTINUE
     RETURN
     END
*****************************************
**          SUBROUTINE HOPKIN          **
*****************************************
     SUBROUTINE HOPKIN(RAD,INALT,SIG,YKT,PLUTO)
     REAL RAD,INALT,SIG,YKT,IM,SM,ID,SD,DELTAZ,LOGYKT
     INTEGER PLUTO
     LOGYKT = ALOG(YKT)
```

```
      IM = EXP(7.889 + .34*LOGYKT + .001226*LOGYKT**2 -
     $.005227*LOGYKT**3 + .000417*LOGYKT**4)
      SM = -EXP(1.574 - .01197*LOGYKT + .03636*LOGYKT**2 -
     $.0041*LOGYKT**3 + .0001965*LOGYKT**4)
      ID = EXP(7.03518 + .158914*LOGYKT + .0837539*LOGYKT
     $**2 - .0155464*LOGYKT**3 + .000862103*LOGYKT**4)
      SD = 7.0 - EXP(1.78999 - .048249*LOGYKT + .0230248*
     $LOGYKT**2 - .00225965*LOGYKT**3 + .000161519*LOGYKT**4)
      INALT = IM + (2.0*RAD*1000000.0*SM)
      DELTAZ = ID + (2.0*RAD*1000000.0*SD)
      SIG = .25*DELTAZ
      RETURN
      END
******************************************
**          SUBROUTINE USAIR            **
******************************************
      SUBROUTINE USAIR(Z,RHO,AIDA)
      REAL Z,RHO,AIDA,LK,TZ,PZ
      IF (Z .LT. 11000) THEN
           LK = -.006545
           TZ = 288.15 - (.006545*Z)
           PZ = 101300.0 * (288.15/TZ)**(-.134164/.006545)
           GO TO 22
      END IF
      IF (Z .LT. 20000) THEN
           LK = 0
```

```
      TZ = 216.65
      PZ = 22690.0*EXP(-.034164*(Z-11000.0)/216.65)
      GO TO 22
   END IF
   IF (Z .LT. 32000) THEN
      LK = .001
      TZ = 216.65 + .001*(Z-20000.0)
      PZ = 5528*(216.65/TZ)**(.034164/.001)
      GO TO 22
   END IF
   IF (Z .LT. 47000) THEN
      LK = .0028
      TZ = 228.65+.0028*(Z-32000.0)
      PZ = 888.8*(228.65/TZ)**(.034164/.0028)
      GO TO 22
   END IF
   IF (Z .LT. 53000) THEN
      LK = 0
      TZ = 270.65
      PZ = 115.8*EXP(-.034164*(Z-47000.0)/270.65)
      GO TO 22
   END IF
   IF (Z .LT. 59000) THEN
      LK = -.0028
      TZ = 265.05-.0028*(Z-53000.0)
      PZ = 54.87*(265.05/TZ)**(-.034164/.0028)
```

```
            GO TO 22
        END IF
        IF (Z .LT. 70000) THEN
            LK = -.0028
            TZ = 248.25-.0028*(Z-59000.0)
            PZ = 25.132*(248.25/TZ)**(-.034164/.0028)
            GO TO 22
        END IF
        IF (Z .GT. 70000) THEN
            PRINT*,'                    WARNING...ALTITUDE ERROR!!!'
        END IF
22      CONTINUE
        RHO = .003484*(PZ/TZ)
        AIDA = (1.458E-6*(TZ**1.5))/(TZ+110.4)
        RETURN
        END
```

EXAMPLE INPUT FILES

FILTER

3500	....	YIELD IN KILOTONS
3	....	NUMBER OF SAMPLES
3.0	....	DISTRIBUTION MOMENT
1.06E+9	....	MASS LOFTED IN KILOGRAMS
.255 13106182.0	....	SAMPLE: MASS (kg), ALTITUDE (m), AND TIME OF COLLECTION (min)
.3118 15758151.5	....	
.142 16246184.0	....	

SEARCH

LOG-SLOPE	STARTING MEDIAN RADIUS	FINAL MEDIAN RADIUS	INCREMENT	NUMBER OF GROUPS
1.5	100.0	300.00	5.0	3.0
1.6	100.0	300.00	5.0	3.0
1.7	100.0	200.00	5.0	3.0
1.8	100.0	200.00	5.0	3.0
1.9	100.0	200.00	5.0	3.0

2.0	20.0	100.00	2.0	3.0
2.1	20.0	75.00	1.0	3.0
2.2	20.0	75.00	1.0	3.0
2.3	10.0	40.00	1.0	3.0
2.4	1.0	30.00	1.0	3.0
2.5	1.0	30.00	1.0	3.0
2.6	1.0	30.00	1.0	3.0
2.7	1.0	30.00	1.0	3.0
2.8	1.0	20.00	1.0	3.0
2.9	1.0	20.00	1.0	3.0
3.0	1.0	20.00	1.0	3.0
3.1	1.0	20.00	1.0	3.0
3.2	1.0	20.00	1.0	3.0
3.3	1.0	10.00	0.5	3.0
3.4	1.0	10.00	0.5	3.0
3.5	0.5	6.00	0.5	3.0
3.6	0.1	3.00	0.2	3.0
3.7	0.1	2.00	0.2	3.0
3.8	0.1	2.00	0.2	3.0
3.9	0.1	1.00	0.1	3.0
4.0	0.1	1.00	0.1	3.0
4.1	0.1	0.60	0.1	3.0
4.2	0.1	0.40	0.1	3.0
4.3	.110	.200	.180	3.0
4.4	.090	.150	.150	3.0
4.5	.080	.120	.120	3.0

4.6	.070	.100	.100	3.0
4.7	.060	.100	.100	3.0
4.8	.050	.080	.005	3.0
4.9	.040	.070	.005	3.0
5.0	.035	.055	.002	3.0
0	0	0	0	0

GLOSSARY OF PROGRAM VARIABLES

Variable Name	Real/Integer	Description
INMASS(25)	Real	Total mass or activity per group
ZZERO(25)	Real	Initial lofted altitude for each mono-size group
R(25)	Real	Mono-size group mean radii
SIGMA(25)	Real	Vertical standard deviation for each mono-size group
TOTMAS(25)	Real	Total mass or activity per sample
TAME(25)	Real	Sample collection times
ALTCHK(25)	Real	Sample altitudes
A(25,25)	Real	Working matrix
B(25,50)	Real	Matrix inversion work area
C(25)	Real	Matrix multiplication solution vector
RHOF	Real	Fallout density (kg/m^3)
G	Real	Acceleration of gravity (m/s^2)

Variable Name	Real/Integer	Description
YKT	Real	Total weapon yield
PLUTO	Integer	Number of samples
MASS	Real	Total mass or activity lofted by the weapon
I	Integer	Counter
TONE	Real	Temporary time storage location
MARK	Integer	Counter
BETA	Real	Distribution log-slope argument
ALPHA1	Real	Starting distribution median radius
ISTEP	Real	Median radius iteration increment
ALPHA2	Real	Final distribution median radius
NUMGRP	Real	Number of mono-size groups
MOMENT	Real	Lognormal distribution moment
RAT	Real	Temporary storage variable
BP	Real	Distribution log-slope
PDINC	Real	Area increment
PDCHK	Real	Incremental variable
Z	Real	Working variable
PD	Real	Working variable
RIGHT	Real	Temporary storage variable
LEFT	Real	Temporary storage variable
FLAG	Integer	Counter

Variable Name	Real/Integer	Description
COLT	Integer	Counter
HOLT	Real	Temporary storage variable
RAD	Real	Temporary storage variable
INALT	Real	Temporary storage variable
SIG	Real	Temporary storage variable
IM	Real	Hopkins' empirical intercept
SM	Real	Hopkins' empirical slope
ID	Real	Conners' empirical intercept
SD	Real	Conners' empirical slope
DELTAZ	Real	Mono-size group vertical thickness (m)
LOGYKT	Real	Natural log of YKT
RHO	Real	Air density
AIDA	Real	Air dynamic viscosity
LK	Real	Atmospheric slope
TZ	Real	Air temperature
PZ	Real	Air pressure
TEMPAL	Real	Temporary storage variable
R2CD	Real	Reynolds number squared times the drag coefficient
REY	Real	Reynolds number
VZ	Real	Particle fall velocity (m/s)
SLPDRG	Real	Slip-drag correction
DELTAT	Real	Particle fall time increment

Variable Name	Real/Integer	Description
J	Integer	Sample counter
T	Integer	Group counter
DUMMY	Real	Temporary storage variable
ALTY	Real	Temporary storage variable
SIGY	Real	Temporary storage variable
ALTZ	Real	Current particle altitude (m)
DZ	Real	Distance traveled by a particle in a time increment DELTAT
SUMMER	Real	Time of fall counter
FIGS	Integer	Flag
DTHOLD	Real	Temporary storage variable
GAUSS	Real	Vertical Gaussian Value at sample altitude at sample time
M	Integer	Counter
K	Integer	Counter
N	Integer	Counter
Q	Integer	Counter
P	Integer	Counter
BF	Real	Temporary storage variable
H	Integer	Counter
F	Integer	Counter
U	Integer	Counter
TEMP	Real	Temporary storage variable
TOTAL	Real	Temporary storage variable

Variable Name	Real/Integer	Description
X	Integer	Counter
Y	Integer	Counter
YOU	Real	Temporary storage variable
WIN	Real	Temporary storage variable
SEAL	Real	Temporary storage variable
CRAB	Real	Temporary storage variable
TAG	Integer	Flag
MINUSE	Integer	Counter
AVERAG	Real	Average of solution vector elements
FISH	Real	Standard deviation of solution vector elements
PIG	Real	Real form of PLUTO
OMEGA	Integer	Program stop flag
QUICK	Integer	New SEARCH parameter flag
DENOM	Real	Long/short search flag
PARTY	Subroutine	Calculates the mean radii for the equal mass/activity groups for each trial distribution
HOPKIN	Subroutine	Calculates the stabilized altitudes and standard deviations for each mono-size group
USAIR	Subroutine	Calculates RHO and AIDA for any given altitude

Bibliography

1. Abramowitz, Milton and Irene A. Stegun. Handbook of Mathematical Functions, Applied Math Series 55. National Bureau of Standards, Department of Commerce, March 1965.

2. Aitchison, J. and J. A. C. Brown. The Lognormal Distribution. Cambridge: Cambridge University Press, 1957.

3. Bigelow, Maj Winfield Scott, Jr. Far Field Fallout Prediction Techniques. PhD Dissertation. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1983.

4. Bridgman, Charles J. and Winfield S. Bigelow. "A New Fallout Prediction Model," Health Physics, 43: 205-218 (August 1982).

5. Byers, Maj Mark. Research Program Manager. Personal Correspondence. Lawrence Livermore National Laboratory, CA, 1-25 November 1985.

6. Colarco, Richard F. A Computer Fallout Model for Operational Studies. MS Thesis. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1980.

7. Conners, Capt Stephen P. Aircrew Dose and Engine Dust Ingestion from Nuclear Cloud Penetration. MS Thesis. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1985.

8. Davies, C. N. "Definitive Equations for the Fluid Resistance of Spheres," The Proceedings of the Physical Society, London, 57: 259-270 (July 1945).

9. Defense Nuclear Agency. Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251, Volume I-Continental U.S. Tests. DNA 1251-1-EX. Washington: Government Printing Office, 1 May 1979.

10. Defense Nuclear Agency. Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251, Volume II-Oceanic U.S. Tests. DNA 1251-2-EX. Washington: Government Printing Office, 1 May 1979.

11. Finnegan, David L. Research Program Manager. Personal Correspondence. Los Alamos National Laboratory, NM, 15-20 November 1985.

12. Freiling, E. C. Fractionation III. Estimation of Fractionation and Radionuclide Partition for Nuclear Debris. USNRDL-TR-680. San Francisco: 12 September 1963.

13. Fuchs, N.A. The Mechanics of Aerosols. New York: The Macmillan Company, 1964.

14. Glasstone, Samuel and Philip J. Dolan. The Effects of Nuclear Weapons (Third Edition). Washington: Government Printing Office, 1977.

15. Heft, Robert E. and William A. Steele. Procedures for the Systematic Separation and Analysis of Radioactive Particles from Nuclear Detonations. UCRL-50428. Livermore: 17 May 1968.

16. Hopkins, Capt Arthur T. A Two Step Method to Treat Variable Winds in Fallout Smearing Codes. MS Thesis. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1982.

17. Hopkins, Maj Arthur T. Development and Validation of a New Fallout Transport Method Using Variable Spectral Winds. PhD Dissertation. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, September 1984.

18. McDonald, J. E. "An Aid to Computation of Terminal Fall Velocities of Spheres," Journal of Meteorology, 17: 463-465 (August 1960).

19. Nathans, M. W. and R. Thews. "The Particle Size Distribution of Cloud Samples," Advances in Chemistry Series, 93: 360-371 (1970).

20. National Oceanic and Atmospheric Administration. U.S. Standard Atmosphere, 1976. National Aeronautics and Space Administration and U.S. Air Force. Washington DC, 1976.

21. Norment, H. G. <u>Deposition Pattern Sensitivity Analysis of the Defense Land Fallout Interpretive Code (DELFIC)</u>, Report DASA-2328, Defense Nuclear Agency, Washington, 1968.

22. Schwenke, T. W., and others. <u>Department of Defense Land Fallout Prediction System, Volume IV. Atmospheric Transport Model</u>. Report DASA-1800-IV, Defense Nuclear Agency. Washington: Government Printing Office, 1967.

23. Way, K. and E. P. Wigner. "The Rate of Decay of Fission Products," <u>Physics Review</u>, <u>73</u>: 1318 (1948).

VITA

James R. Felty was born on [redacted] in [redacted], [redacted]. He graduated from Blue Mountain High School in [redacted] and entered the United States Military Academy Preparatory School (USMAPS) at Fort Belvoir, Virginia in 1971. Upon his graduation from USMAPS in 1972, he entered the United States Military Academy at West Point, New York. He graduated from the Military Academy in June of 1976 with a B.S. degree. His Army assignments as a Field Artillery officer included tours of duty at Fort Benning, Georgia with the 197th Infantry Brigade (Separate); Fort Sill, Oklahoma for the Field Artillery Officers' Basic and Advanced courses, and the Nuclear Target Analysis Course; Camp Essayons, Korea with the Second Infantry Division Artillery; and finally, Fort Bliss, Texas with the Third Armored Cavalry Regiment where he commanded the Howitzer Battery in First Squadron. Prior to leaving Fort Bliss permanently, he was sent to Fort Leavenworth, Kansas for temporary duty to attend the Combined Arms Services Staff School. Captain Felty was assigned to the Air Force Institute of Technology's Nuclear Effects Masters Degree program in August of 1984.

Permanent address: [redacted]

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

AD-A172 966

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; Distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): AFIT/GNE/PH/86M-4

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: School of Engineering

6b. OFFICE SYMBOL (If applicable): AFIT/EN

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State and ZIP Code): Air Force Institute of Technology, Wright-Patterson AFB, OH 45433

7b. ADDRESS (City, State and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State and ZIP Code):

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE (Include Security Classification): See box 19

12. PERSONAL AUTHOR(S): James R. Felty, B.S., Captain, USA

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM ____ TO ____	1986, March	126

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.
01	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Nuclear Clouds, Airborne Filter Sampling, Redwing-Zuni, Fallout, Nuclear Cloud Samples

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: A NUMERICAL METHOD FOR UNFOLDING THE STABILIZED NUCLEAR CLOUD PARTICLE DISTRIBUTION

Thesis Chairman: Dr. Charles J. Bridgman
Professor of Nuclear Engineering
Department of Engineering Physics

Abstract continued on reverse.

Approved for public release: IAW AFR 190-1
Lynn E. Wolaver 9 May 86
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Dr. Charles J. Bridgman	513-255-2012	AFIT/ENP

DD FORM 1473, 83 APR   EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

Block 19 continued.

Abstract

This study developed a numerical method of unfolding the particle size distribution of the stabilized nuclear cloud from airborne filter sample data. A stabilized nuclear cloud is modeled using a trial particle size distribution that is positioned in the atmosphere by empirical relationships developed by Hopkins and Connors. Davies-McDonald fall mechanics are used to model the falling particles in the nuclear cloud. The amount of mass at each sample altitude, at each sample time is calculated from the cloud model and compared to the amount of mass found in the actual cloud samples. When the calculated masses equal the actual masses, the particle distribution used to construct the stabilized cloud is the correct one. A computer code for this numerical analysis is also presented.

The computer code is tested using hypothetical filter sample data constructed from a known particle size distribution. Additionally, an input parameter sensitivity analysis is conducted.

Actual nuclear cloud sample data from the Redwing series, shot ZUNI is analyzed using this numerical method of airborne nuclear cloud sample analysis. The outcome of the ZUNI sample analysis is somewhat inconclusive in that it does not pinpoint a distribution. However, based on the results of the model sensitivity analysis, the ZUNI sample analysis indicates that the particle size distribution of the stabilized ZUNI cloud may be lognormal with a log-slope between 2.9 and 3.9 but is definitely not less than 2.7 nor greater than 5.0.

Finally, the the theory for an alternative method of airborne sample analysis is presented. This method uses the relative number of particles of each size found in airborne samplesto unfold the stabilized nuclear cloud particle size distribution.